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Spatial Distribution and Sequential Sampling of the Rice Water Weevil, Lissorhoptrus Oryzophilus Kuschel, in Louisiana.

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SPATIAL DISTRIBUTION AND SEQUENTIAL SAMPLING OF THE RICE WATER WEEVIL, *Lissorhoptrus oryzophilus*, KUSCHEL IN LOUISIANA

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ABSTRACT

Studies were conducted in Louisiana to determine the spatial and temporal distribution of rice water weevil (RWW), *Lissorhoptrus oryzophilus* Kuschel, adults, eggs, larvae and pupae in drill-seeded rice. In addition, three sequential sampling plans, Kuno's fixed precision sequential sampling plan, the sequential probability ratio test (SPRT), and 2-SPRT, were developed and evaluated to establish an accurate and economically efficient sampling plan for RWW larvae in drill-seeded rice in Louisiana.

Values obtained for the aggregation indices, b, from Taylor's power law, β, from Iwao's patchiness regression and, k, from the negative binomial distribution indicated that RWW larvae were nearly randomly distributed regardless of sample date. Iwao's patchiness regression and the negative binomial distribution modeled larva populations better than Taylor's power law. A common k (kc) of 13.63 was determined from the larva data.

Monte Carlo simulations of Kuno's sampling plan provided actual precision levels that were higher than those specified for the simulation. Kuno's sampling plan required $\approx$ 6 and 14 samples to estimate RWW larva economic threshold at the specified precision levels of D=0.20 and 0.30, respectively. Monte Carlo simulation of the SPRTs indicated that the 2-SPRT generally required fewer samples to make terminating decisions for RWW larvae management compared to the SPRT, however, only the SPRT maintained Type I and II error rates below the specified error rate of 0.10. The SPRT and 2-SPRT required an average of 2.43 and 2.59 samples to make

terminating management decisions at RWW larva economic threshold. The SPRTs required the least sampling effort and would substantially decrease sampling effort compared to larva sampling programs currently used to make RWW management decisions in Louisiana.

Spatial autocorrelation analysis indicated that all RWW developmental stages exhibited significant spatial dependence. Spatial correlograms and spatial density maps suggested that 2 to 13 m^2 patches were exhibited by all RWW life stages. This spatial phenomenon was not detected by Taylor's power law, Iwao's patchiness regression or k from the negative binomial distribution.

INTRODUCTION

Rice is the staple food for nearly 2/3 of the world's population. Rice production will need to increase by 50% by the year 2020 in order to keep pace with the current population growth rate (Lu & Chang 1980, Grayson et al. 1990). Rice was first cultivated in south-central Asia as early as 6900 B.C. (Lu & Chang 1980). Rice producing regions of the world now exceed 100 countries with over 142 million hectares of rice land producing 376 million metric tons (Lu & Chang 1980). Lu & Chang (1980) reported that the world rice hectarage in 1978 was second only to wheat, and the yield per hectare second only to maize. As with many cultivated crops, rice is subject to disease, weed, and arthropod pest pressure. Ninety percent of the world's rice production occurs in subtropical or tropical areas (Woodburn 1990). In such environments the growing season is longer, annual rainfall is higher, plant and animal species diversity is greater, and pest pressure is higher than in temperate environments. Way et al. (1991) reported that insect pests accounted for rice yield losses of 26%, worldwide. Rice growers have relied on chemical pesticides to control pest problems more heavily than any other crop. Woodburn (1990) reported that rice was the single most important crop in agrochemical consumption, which in 1988 was valued at nearly 2.5 billion dollars. Further, Woodburn (1990) reported that insecticide for control of rice pests during the 1988 growing season cost growers 910 million dollars.

Although the United States represents only 1.4% of the world rice hectarage, yield per hectare represents some of worlds highest (Lu & Chang 1980, Way 1990). Rice production in this country began around 1609 in Virginia (Lu & Chang 1980). Rice in the United States is grown in Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas, with 1991 acreage exceeding 2.8 million

(Anonymous 1992). However, the states of Arkansas, Louisiana, Texas, and California grow nearly 90% of the rice produced in the United States (Anonymous 1992).

Numerous insect pests can cause significant yield loss in rice grown in the United States. These pests include the rice water weevil, *Lissorhoptrus oryzophilus* Kuschel; the rice stink bug, *Oebalus pugnax* (F.); the fall armyworm, *Spodoptera frugipurda* (J.E. Smith); the rice leaf miner, *Hydrellia griseola* (Fallen); the least skipper, *Ancyloxypha numitor* (F.); the rice stalk borer, *Chilo plejadellus* Zincken; and the sugarcane borer, *Diatrea saccharalis* (F.) (Smith 1983). The most important of these is the rice water weevil, *L. oryzophilus* (RWW), which causes economic damage to rice in all rice growing areas of the United States (Smith 1983, Smith et al. 1986, Way 1990).

Accurate methods for monitoring pest density are central aspects of integrated pest management programs (Nyrop & Binns 1991). Development of efficient and reliable pest sampling methods require knowledge of the pest species' spatial distribution (Binns & Nyrop 1992, Nyrop & Binns 1991). Appropriate information regarding RWW spatial distribution is not available in Louisiana. Sooksai & Tugwell (1978) reported that adult feeding scars in Arkansas rice fields were clumped near levees soon after permanent flood, but later in the growing season were uniformly distributed. Morgan et al. (1989) indicated that leaf scar density was at best a crude predictor of RWW larval density. Also, rice production and RWW biology in Arkansas are sufficiently different from those in Louisiana that RWW spatial distributions may also differ. Work by Robinson et al.(1978) indicated that the distribution of RWW larvae in Louisiana were clumped. This (Robinson et al.1978) study was intended to provide preliminary data for the development of RWW

sampling plans. They collected data from sampling units of different sizes and used unspecified sampling method(s) (stratified, random etc.). These data are therefore inadequate for precisely describing RWW spatial distribution. Cave et al. (1984) investigated RWW spatial distribution in Louisiana in order to select rice varieties resistant to RWW. In their study, plot size was small and plant density was considerably lower than that used for commercial rice production. Insect spatial distributions are influenced by host plants and other biotic and abiotic factors, and are inherently dynamic and species specific (Taylor 1984). Thus, for sampling programs to function effectively, spatial distributions of pest species should be assessed under conditions for which the sampling program will be used. Spatial distribution of RWW adults, eggs, and pupae have not been studied.

Rice water weevil management decisions in Louisiana are currently based on two sampling methods: indirect estimation of RWW larva density based on the density of adult leaf feeding scars, and direct estimation based on larva sampling (Smith et al. 1986). Although intrinsically less time consuming, estimating larval density based on adult leaf feeding scar density is not as accurate as larval sampling, and is useful only for crude estimates of larval density (Tugwell & Stephen 1981, Morgan et al. 1989). In fact, larval density based on leaf scar counts in Louisiana are usually followed by larval sampling (Smith et al. 1986). Sampling rice plants and surrounding soil for larvae provides accurate estimates of larval density, but is time consuming and costly. Using current recommendations of 10 core samples/field for rice grown in Louisiana, we estimate that 40 to 50 minutes are required to sample a single field. In addition, early instar larvae are small and difficult to separate from other organisms and debris in the sample. Both methods used in Louisiana are based on fixed sample size: i.e. a fixed number of samples are required to estimate

population size regardless of pest density (Smith et al. 1986). These types of plans usually require greater sampling effort and are less cost efficient than sequential sampling plans such as those based on sequential probability ratio tests (i.e. 2-SPRT, SPRT) (Nyrop & Binns 1991). The objectives of this study were to:

1. Determine the spatial and temporal distribution of rice water weevil eggs, larvae, pupae, and adults in drill-seeded rice.
2. Develop and evaluate three sequential sampling plans for rice water weevil larvae infesting drill-seeded rice in Louisiana.
3. Describe the spatial dispersion patterns of RWW life stages in drill-seeded rice using spatial autocorrelation analysis and compare the results of that analysis with the results of analyses using traditional statistical methods for determining organism spatial distributions.

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LITERATURE REVIEW

The rice water weevil (RWW), Lissorhoptrus oryzophilus Kuschel, is one of the most destructive insect pest of rice in all rice growing areas of the United States (Way 1990). Adults and larvae RWW can cause damage to rice. Adult RWW damage rice by chewing longitudinal slits from the rice leaf epidermal tissue, and occasionally by feeding on the developing rice seed (Isely & Schwardt 1934, Douglas & Ingram 1942, Smith 1983). However, economic damage is usually associated with RWW larvae feeding on the plant roots (Way et al. 1991, Way 1990, Smith 1983 & 1986, Bowling 1967). Larval feeding causes plant stunting, lodging, stand reduction, prolonged development, and yield reduction (Bowling 1967, Smith 1983). Yield losses of 10 to 50% have been reported in Louisiana (Smith 1983, USDA 1989). A 45 kg/Ha reduction in rice grain for every larva found in a 10 cm sample has been reported in Louisiana (Way et al. 1991).

Taxonomy: The rice water weevil was originally described as *Bagous simplex* by Thomas Say in 1831 (Kuschel 1951). LeConte (1876) removed the RWW from the genus *Bagous* and placed it in his newly erected genus *Lissorhoptrus*. However, Kuschel (1951) stated that the type for *B. simplex* Say had been lost sometime before LeContes' treatise of this group. Kuschel was faced with two problems. First, if the type for *B. simplex* Say was lost before LeContes' revision, from what specimens did LeConte base his decisions (ie. is LeContes' *Lissorhoptrus simplex* the same as Says' *Bagous simplex*)? Second, Kuschel, in his revision of the genus *Lissorhoptrus*, determined that the RWW consisted of two similar species; ergo, which of the two water weevil species should retain the original name. Although unable to examine the holotype for *B. simplex* Say, Kuschel did examine several type species that LeConte gave as synonyms of *L. simplex*, including LeContes' *L. simplex*. Of these species, Kuschel determined that *B. egenus* Gyll. and *L. apiculatus* LeConte were

synonymous with LeContes' *L. simplex*. Additionally, Kuschel found that Thomas Say sent an example of the series he used to describe *B. simplex* to Gyllenhal for examination at the time Gyllenhal described *B. egenus*. Kuschel concluded with the opinion of Dr. J. Bequaert that *B. simplex* and *B. egenus* Gyll. were synonymous, and that this species [*L. simplex* (Say)] did not represent the economically important species of the two water weevils. Because of the law of priority set forth by the International Code of Zoological Nomenclature, the water weevil, synonymous with *B. egenus*, retained the name *L. simplex* (Say), while Kuschel named the economically important water weevil *L. oryzophilus* Kuschel. Both species are morphologically similar and occur in similar habitats, but may be distinguished by the following characters of *L. oryzophilus* given by Kuschel (1951): Postibia without praemucrus; mucrus thick and bifid with a robust tooth basal and posterior, subequal to mucrus; tergite VII deeply scooped.

Until Kuschels' (1951) revision of the genus *Lissorhoptrus*, gender determination was impossible because *L. simplex* unknowingly consisted of two species. Kuschel (1951) reported that for *L. oryzophilus* the posterior edge of the pygidium was straight in the male and indented in the females, and the shape of the male mucro was large and bifurcate. However, Kuschel (1951) did not indicate the state of the female mucro. Everett & Newsom (1964) found that the abdominal character given by Kuschel was difficult to use because the elytra typically covered the pygidium and to expose this area required time and skill. Everett & Newsom (1964) found that female sternites III & IV at the midline were flat to convex, while those of the male were concave, and that an area on sternite VII was raised and posteriorly rounded in the female, while straight across in the male. They also found that the post-tibial mucro was simple in females and bifurcate in males.

Biology: Rice water weevil biology and ecology have been studied by a number of researchers (Bowling 1972, Cave & Smith 1983, Everett & Trahan 1967, Gifford & Trahan 1966, Grigarick & Beards 1965, Halzlip & Tugwell 1983, Isely & Schwardt 1934, Muda, et al. 1981, Nilakhe 1977, Morgan et al. 1984). However, because of the taxonomic uncertainty of the RWW prior to Kuschels' (1951) revision of the genus *Lissorhoptrus*, biological studies prior to that time should be interpreted cautiously. Additionally, two disparate RWW populations exist: a sexually reproducing population in the southeastern United States, and a parthenogenetically reproducing population in California, Korea, and Japan (Grigarick & Beards 1965, Tsuzuki et al. 1984, Smith 1983).

Rice water weevil seasonal history generally occurs as follows: adults overwinter predominantly in leaf litter and bunch grasses (Gifford & Trahan 1969), but can also be found in Spanish moss and fine matted grass (Tucker 1912). Indirect flight muscles degenerate after adults find a suitable overwintering site (Muda et al. 1981). Overwintering adults enter a state of diapause (Nilakhe 1977). Indirect flight muscle regeneration occurs during the spring before adults migrate from their overwintering site (Muda et al. 1981). Morgan et al. (1984) reported that the temperature threshold for RWW flight muscle regeneration was 18°C, and that flight muscle regeneration increased with increasing temperatures, but at 24°C high adult mortality occurred. Adults migrate to locations where suitable food/oviposition sources occur. Flight muscles degenerate once adults have located a suitable location restricting them to the immediate area (Muda et al. 1981).

The RWW is native to North America (Kuschel 1951), and can develop on hosts other than rice. Plants reported as acceptable hosts for RWW include several species of grasses and sedges (Webb 1914, Lange et al. 1959, Isely & Schwardt 1934,

Newell 1913). Webb (1914) reported that in the field, RWW larvae were found infesting *Paspalum larranagae* Arech., *P. plicatulum* Michx., and *Cyperus flavicornus* Michx. Isely & Schwardt (1934) found that *Echinochloa crusgalli* Beauv. in Arkansas was commonly infested with RWW.

Rice water weevil adult females oviposit pearly white, elliptical, 0.8mm long eggs in the submerged leaf sheaths, or more rarely, in the root tissue of rice plants (Grigarick & Beards 1965). Eggs hatch in 4 to 9 days under field conditions (Smith 1983). Neonates feed within the leaf sheath for a short time before exiting the sheath and moving to the roots to feed (Grigarick & Beards 1965). Larva are translucent white, legless grubs possessing paired dorsal hooks on abdominal segments II through VII. The dorsal tracheal hooks are believed to aid in movement in and around the rice root system and to function in a respiratory capacity (Isely & Schwardt 1934). Normal spiracles, however, occur on the mesothoracic and first and ninth abdominal segments (Isely & Schwardt 1934). The larvae go through four instars completing development at 27°C in approximately 27.5 days (Cave & Smith 1983). Pupation takes place in water-tight mud cells attached to rice roots (Isely & Schwardt 1934), and adults eclose in about seven days at 27°C (Cave & Smith 1983). First generation adults have well developed flight muscles and can migrate to new host plants (Muda et al. 1981). The number of RWW generations per year is dependent on geographic location. Gifford & Trahan (1966) reported two complete and a partial third generation in Louisiana. Muda et al. (1981) reported one complete and a partial second generation in Arkansas.

Management: Cultural control of RWW by water management was first proposed by Screven and endorsed by Howard in 1881 (Tucker 1912). Water management in rice fields has effectively controlled RWW larva populations (Tucker

1912, Newell 1913, Webb 1914, Isely & Schwardt 1934, Morgan et al. 1989, Quisenberry et al 1992, Hesler et al. 1992). Controlling RWW larvae using water management requires draining the rice field when the economic threshold for RWW larvae has been reached and allowing the soil to dry until soil-cracking is apparent. Problems associated with this practice include reduced rice yield and weed control (Newell 1913), increased water costs, (Isely & Schwardt 1934), loss of fertilizer, ineffective control when reflooded to soon (Smith 1983, Quisenberry et al. 1992), rainfall may prevent fields from drying (Quisenberry et al. 1992), and appropriate timing of drainage may be difficult to establish (Hesler et al. 1992). Quisenberry et al. (1992) reported, however, that when compared to carbofuran treated plots, water management provided higher net returns and with the pending loss of carbofuran, water management could be an economical RWW control tactic.

Chemical control was probably not used until the middle 20th century when Whitehead (1954) reported good RWW control using organochlorines, although Tucker (1912) suggested using a poison in 1912, and Newell (1913) proposed the use of arsenicals for Adult RWW control. Organochlorines, in the 1950's and early 1960's, provided effective RWW control (Bowling 1967); however, aldrin treated rice seed was the preferred method for RWW control (Bowling 1967, Smith 1983). Aldrin-resistant RWW populations were discovered in the 1960's (Everett et al. 1964, Bowling 1968), and led to the testing of many carbamate and organophosphate insecticides (Gifford et al. 1968, Bowling 1967). Many of the tested compounds controlled RWW, but were directly phytotoxic or caused seedling damage when applied with herbicides (Smith 1983, Gifford et al 1968, Bowling & Flinchum 1967). Granular carbofuran was found to provide effective RWW control with little or no detrimental effects on rice (Bowling 1967, Gifford & Trahan 1968, Smith & Tugwell

1975). Carbofuran applied as a 3% granular continues to provide effective control of the rice water weevil (Smith 1983, Muegge et al. 1993).

Economic pressure and increasing environmental concerns have elicited the need for more cost effective and environmentally conscience pest management. Methods for efficiently and accurately monitoring pest populations are central to integrated pest management (IPM) theory (Nyrop & Binns 1991). Economic thresholds reported for Arkansas, Louisiana, and Texas are 10, 5, and 5 larvae/sample, respectively (Smith et al 1986, Way et al. 1991, Drees et al. 1993). Two methods are recommended for making RWW management decisions in Louisiana; indirect estimation of RWW larval density based on adult leaf feeding scar density, and direct estimation based on larval sampling (Smith et al. 1986). Soil sampling to estimate RWW larval density involves the use of a soil core sampler to remove a quantity of rice roots and surrounding soil. The sample is then placed in a bucket fitted with a 40-mesh screen and submerged in water. The soil and larvae are washed from the rice roots, and after a few seconds the larvae float to the surface where they can be counted (Bagent & Seilhan 1993). This method has been used frequently for determining RWW larval density, but problems associated with this method include inefficient larva recovery, larvae movement due to lack of food source, and the inherent time and associated cost involved with this sampling procedure (Way et al. 1991). Using current recommendations of 10 core samples/field for rice grown in Louisiana, we estimate that 40 to 50 minutes are required to sample a single field.

Sooksai & Tugwell (1978) developed the leaf-scar sampling technique. Sooksai & Tugwell (1978) and Morgan et al. (1989) reported that leaf scar density accounted for 46% and 32% of the variation in RWW larva density, respectively.

Although this method is intrinsically less time consuming, estimating larval density based on adult leaf feeding scars is not as accurate as larval sampling, and is useful only for crude estimation of larval density (Tugwell & Stephen 1981, Morgan et al. 1989). In fact, larval density based on leaf scar counts in Louisiana are usually followed by larval sampling (Smith et al. 1986). Sampling plans have been developed based on leaf scar density (Tugwell & Stephen 1978 & 1981, Way et al. 1991). Economic thresholds (ET) of 60, 50, 50, and 20% leaves scarred have been reported for Arkansas, Louisiana, Texas, and California, respectively (Tugwell & Stephen 1981, Smith 1986, Way et al. 1991, Drees et al. 1993). The lower ET established for adult RWW feeding scars in California occurs because only female RWW are found there (Way et al. 1991).

Many problems are associated with the development of rice water weevil sampling and decision making programs. Some of these problems include the variety of agronomic practices within and between rice growing states in the United States, and the general biology and biogeographic differences associated with the rice water weevil. In order to reduce RWW populations, management strategies must be designed with these problems in mind.

Both methods for estimating RWW economic threshold in Louisiana are based on fixed sample size: i.e. a fixed number of samples are required to estimate population size regardless of pest density. (Smith et al. 1986). These types of plans usually require greater sampling effort and are less cost efficient than sequential sampling plans such as those based on sequential probability ratio tests (i.e. 2-SPRT, SPRT) (Nyrop & Binns 1991). Consequently, sequential sampling plans have seen extensive use in pest management (Fowler & Lynch 1987a,b).

A sequential sampling plan based on adult feeding damage has been developed for RWW management in Arkansas (Tugwell & Stephen 1978, 1981). However, rice production practices and RWW biology differ sufficiently among rice producing states that methods used in one state may not be applicable in another. Cave et al. (1984) developed a sequential sampling plan for RWW larvae in Louisiana based on Green's fixed precision sequential sampling plan (Green 1970). However, the objective of their study was to aid in the identification of RWW resistant rice lines, and was not developed under conditions used in commercial rice production. Plant density in the Cave et al. (1984) study was $1/0.1m^2$. Plant density in the present study was ca. $20/0.1m^2$; the density recommended for commercial rice production in Louisiana (Anonymous 1987). This plan may therefore not be useful for making RWW management for commercially grown rice in Louisiana.

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CHAPTER I

SPATIAL DISTRIBUTION OF RICE WATER WEEVIL, *Lissorhoptrus oryzophilus* KUSCHEL (COLEOPTERA: CURCULIONIDAE), LARVAE IN LOUISIANA RICE FIELDS

Introduction

The rice water weevil (RWW), *Lissorhoptrus oryzophilus* Kuschel, is the most destructive insect pest of rice in the United States. Adult RWW damage rice by chewing longitudinal slits from the rice leaf epidermal tissue, and occasionally by feeding on the developing rice seed (Isely & Schwardt 1934, Douglas & Ingram 1942). However, economic damage is caused by RWW larvae feeding on the roots of rice plants (Way et al. 1991). Root feeding by RWW larvae can cause lodging, yellowing, stunting, and reduced yield (Bowling 1967). Root damage caused by larval feeding can result in yield losses of 10 to 50% in Louisiana (Smith et al. 1986, USDA 1989).

Accurate methods for monitoring pest density are central aspects of IPM programs (Nyrop & Binns 1991). Development of efficient and reliable pest sampling methods require knowledge of the pest species' spatial distribution (Binns & Nyrop 1992, Nyrop & Binns 1991). Appropriate information regarding RWW spatial distribution is not available in Louisiana. Sooksai & Tugwell (1978) reported that soon after permanent flood adult feeding scars in Arkansas rice fields were clumped near levees, but were uniformly distributed throughout the remainder of the fields. Morgan et al. (1989) indicated that leaf scar density was at best a crude predictor of RWW larval density. Also, rice production and RWW biology in Arkansas are sufficiently different from those in Louisiana that RWW spatial distributions may also differ. Work by Robinson et al. (1978) indicated that the distribution of RWW larvae

in Louisiana were clumped. This study was intended to provide preliminary data for the development of RWW sampling methods. Data were collected from sampling units of different sizes and sampling method(s) (stratified, random etc.) were not specified. This data is therefore inadequate for precisely describing RWW spatial distribution. Cave & Smith (1984) investigated RWW spatial distribution in Louisiana in order to aid selection of rice varieties resistant to RWW. In their study, plot size was small and plant density was considerably lower than that used for commercial rice production. Insect spatial distributions are influenced by host plants and other biotic and abiotic factors, and are inherently dynamic and species specific (Taylor 1984). Thus, for sampling programs to function effectively, spatial distributions of pest species should be assessed under conditions for which the sampling program will be used. The purpose of this research was to determine the spatial distribution of RWW larvae under conditions likely to be encountered in the production of drill seeded rice in Louisiana.

Materials and Methods

All research was conducted during 1993 and 1994 at the Rice Research Station, near Crowley, Louisiana. The rice cultivar "Lemont" was drill-seeded to fields measuring 23.8 x 7.5 m and 24.4 x 7.5 m on 21 May 1993 and 9 April 1994, respectively. Rice was planted at 112 kg/ha with 17.5 cm row spacing. Thirty-five cm alleys were placed longitudinally every 1.22 m to facilitate data collection. Nitrogen (13:13:13 N-P-K) was pre-plant incorporated at 50.6 kg/ha and broadcast

pre-flood at 101.2 kg/ha (21:0:0 N-P-K). Propanil was applied pre-flood in 1993 and 1994 at 3.4 kg AI/ha for weed control. Benomyl was applied aerially post-flood in 1993 at a rate of 0.56 kg AI/ha to suppress rice blast.

A stratified sampling scheme was used both years. Fields were divided into 40, 2.31 m^2 and 400, 0.37 m^2 quadrates in 1993 and 1994, respectively. Rice water weevil larvae were sampled weekly (9 July-6 August 1993 and 2 June-30 June 1994) beginning three and one wks after permanent flood in 1993 and 1994 fields, respectively. A single randomly selected soil/plant sample was taken from each quadrate using a 10.2 x 10.2 (ht. x dia.) cm core sampler. Each sample was placed into a plastic bag, taken to a RWW extraction shed, and washed through a funnel fitted with wire screen into a 60 mesh screen sieve. Collected larvae and pupae were floated in a saturated NaCl solution, removed, and placed into labeled scintillation vials filled with 70% EtOH. Vials with larvae and pupae were taken to the laboratory where they were sorted by developmental stage according to head capsule size (Cave & Smith 1983) and counted.

Optimum sample unit area was determined by finding the smallest sampling area where sampling variance was minimized (Israel & Abraham 1964). This was accomplished by dividing the field into 16 plots composed of 25, 0.37 m^2 quadrates. Quadrates within each plot were combined to give sampling areas of 0.74, 1.5, 3.3, 5.9, and 9.3 m^2. Observations were summed and variances determined for each of the five sampling areas across the 16 plots. Data were log transformed before variances

were plotted against plot sizes. The smallest sample unit area where sampling variance stabilized was chosen as the sampling area for all subsequent analyses.

Sample sums for non-transformed data were compared to the negative binomial and Poisson distributions using distribution fitting software (Bestfit®, 31 Decker Road; Newfield, NY 14867) and tested for goodness of fit using the χ^2 statistic. Maximum likelihood estimation of k and k_c was determined following procedures of Bliss and Fisher (1953).

Rice water weevil spatial distribution was also described by fitting the data to Taylor's power law and Iwao's patchiness regression (Taylor 1961, Iwao 1968). Taylor's power law $s^2 = a\bar{x}^b$ was log transformed to yield the linear equation:

$$\log s^2 = a + b \log \bar{x}$$

where s^2 = the sample variance; a = a scaling factor related to sample size; b = a species specific measure of aggregation; and $\bar{x}$ = the sample mean (Taylor 1961). The larval data were then fitted to the log transformed equation.

Iwao's patchiness regression (1968) is given by the equation: $\dot{x} = \alpha + \beta m$, where α= an index of basic contagion; β = a density-contagioness coefficient; m = the population mean, and $\dot{x}$ = Lloyd's (1967) mean crowding index. Lloyd's mean crowing index is expressed by the equation:

$$\dot{x} = m + \left(s^2/m - 1\right)$$

where m = the sample mean; and s^2 = the sample variance. Iwao's patchiness regression parameters were determined by regressing Lloyd's mean crowding index on the sample mean.

The parameters k from the negative binomial distribution, b from Taylor's power law, and β from Iwao's patchiness regression are considered aggregation indices (Taylor 1961 & 1984, Iwao 1968). The parameter k of the negative binomial distribution describes clumped ($0 \leq k \leq 8$) through more random ($8 \leq k \rightarrow \infty$) populations. The parameters b and β describe distributions ranging from near regular ($0 < b$ &β < 1), through random (b & β$=1$) and increasingly aggregated populations ($1 < b$ &β $\rightarrow \infty$). (Southwood 1989).

Results

We had intended to determine the spatial distribution of all RWW instars. However, density of early instars was too low to conduct meaningful analysis. Therefore, data were pooled across instars, and distribution was determined for the total number of RWW larvae. Sampling variance based on 1994 data decreased with increasing sampling unit area (Fig. 1.1). No significant difference between the ratio of the largest (s_1^2) and smallest (s_2^2) sampling variances was found

$(s_1^2 / s_2^2 = 1.86281;\ 1 / F_{(df=15,15)} = 0.416667, F_{(df=15,15)} = 2.40)$, indicating that no significant differences occurred among sample units of any size.

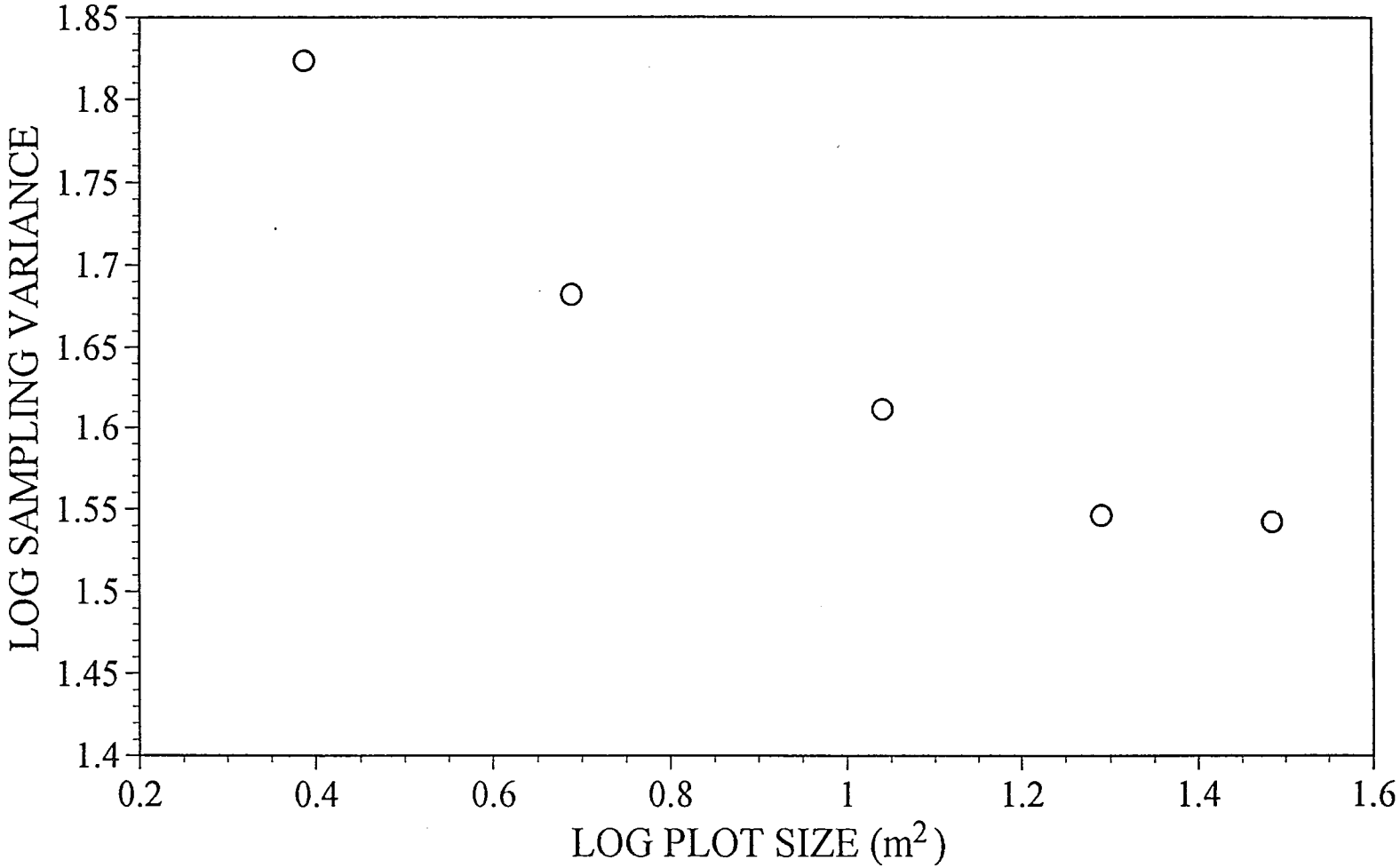

Figure 1.1. Relationship between sampling variance and sampling unit size for total RWW larvae.

Values for k ranged from 11.79 to 230.4 in 1993 and from 7.93 to 29.77 in 1994 (Table 1.1). Rice water weevil larval distributions deviated significantly from the negative binomial distribution on three of nine sampling dates over the two years. Values of k varied considerably across collection dates, however, maximum likelihood estimation yielded a common k (kc=13.63) which did not significantly differ from the expected value for the negative binomial distribution (Table 1.1). Larval distributions deviated significantly from the Poisson distribution on all dates except for August 6, 1993. Rice water weevil larval populations for this date gave a slightly better fit to the negative binomial distribution.

Fitting the data to Taylor's power law gave significant regressions to all four of the 1994, but none of the 1993, sample dates (Table 1.2). The lack of fit to the 1993 data may have resulted from fewer observations compared to 1994 data. Even on sampling dates where the regression was significant, Taylor's regression model explained little of the sample variance. Coefficients of determination were less than 0.48 on all but two sampling dates. Taylor's power law regression gave a significant fit to the data over all sample dates, accounting for 77.9% of the sample variance (Fig. 1.2).

Iwao's patchiness regression significantly fit the RWW larval data on all but one date (Table 1.2). Coefficients of determination ranged from 0.654 to 0.910 and from 0.740 to 0.974 in 1993 and 1994, respectively. Iwao's regression fit the data over all sample dates well, with 98.1% of the sample variance explained by the model

Table 1.1. The parameters $\bar{x}$, k and common k, n, and χ^2 test of fit to the negative binomial distribution for total RWW larvae by date and over all dates and both years.

Year	Date	$\bar{x}$ [1]	k [2]	(k_c) [3]	n [4]	(χ^2) [5]
1993	July 9	33.17	28.28		5	44.18*
	July 16	23.92	31.22		5	32.89*
	July 23	14.55	11.79		5	30.68*
	July 30	4.8	65.8		5	6.356
	Aug 6	1.8	230.4		5	4.732
1994	June 9	9.91	29.77		25	6.163
	June 16	28.92	13.02		25	26.89
	June 23	18.32	11.62		25	18.02
	June 30	6.81	7.93		25	9.615
Common k		16.49		13.63	9	11.25

1. mean RWW larvae per core sample.
2. negative binomial parameter for each collection date.
3. common k determined from all collection dates for 1993 and 1994.
4. number of samples unit areas (individual collection dates) used to determine k and number of samples (each collection date) used to determine common k.
5. * indicates that data significantly deviated from the negative binomial distribution ($P<0.05$).

Table 1.2. Aggregation indices for Taylor's power law (b) and Iwao's patchiness regression (β), and the coeffiecient of determination and F statistics for RWW larvae collected by date in 1993 and 1994.

	Taylor's Power Law			Iwao's Patchiness Regression		
Date	b[1]	r^2	F value [(2)]	β[1]	r^2	F value[(2)]
			1993			
July 9	0.931	0.082	0.267	0.984	0.910	30.23*
July 16	0.089	0.001	0.003	0.847	0.654	5.669
July 23	0.658	0.060	0.191	0.989	0.872	20.54*
July 30	1.658	0.480	2.770	0.989	0.872	20.54*
Aug 6	2.941	0.619	4.865	2.074	0.840	15.80*
			1994			
June 9	1.184	0.241	7.299*	1.062	0.737	64.33*
June 16	0.910	0.295	9.647*	0.979	0.974	844.8*
June 23	1.002	0.238	7.205*	0.998	0.919	259.1*
June 30	1.634	0.666	45.87*	1.192	0.911	236.2*
Pooled Data	1.283	0.776	427.4*	1.036	0.981	6441.7*

1. Slopes were not significantly different from the Poisson slope of one (T-Test; $\underline{P} \leq 0.05$).
2. * Indicates significant regression model ($\underline{P} \leq 0.05$).

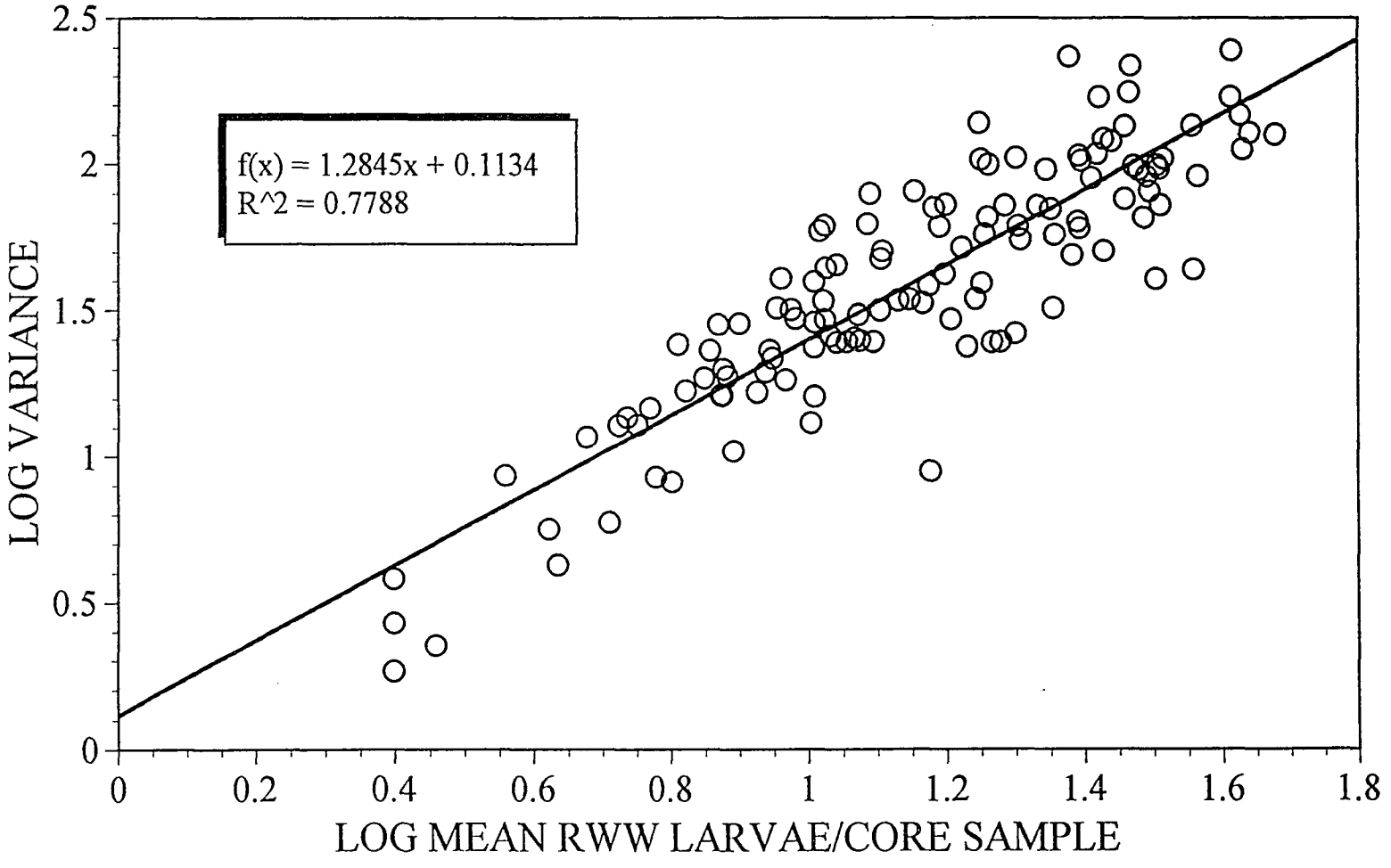

Figure 1.2. Taylor's power law regression for total RWW larvae over all collection dates in 1993 and 1994.

(Fig. 1.3). The values obtained for the aggregation indices; "*b*" of Taylor's power law, and "β" of Iwao's patchiness regression, by date and pooled across sample dates, were not significantly different from the Poisson slope of one (Table 1.2). Iwao's patchiness regression was also a better predictor of pooled larval variance than Taylor's power law (Fig. 1.4), indicating that Iwao's patchiness regression may be more useful than Taylor's power law for developing RWW sampling plans.

Discussion

Although choice of a sampling unit area was not statistically restricted, we chose the larger 5.9 m^2 sampling area. This was done because larger sampling areas tend to reduce edge effects. This could be important, since RWW adults and larvae have been reported to occur in greater densities along field edges (Smith et al. 1986). Larger sampling variances would also increase sampling effort (to maintain the required proficiency) and thus increase sampling cost (Southwood 1989).

Values of *k* by date from our data indicate that RWW larvae followed a near random distribution initially, becoming slightly clumped over time. Values of *k* for RWW larvae reported by Robinson et al. (1978) were generally lower than those reported here, indicating a more clumped distribution than our data would suggest. Differences in *k* values observed between the two studies may be explained, at least in part, by methodological differences between the studies. Sample unit size, mean density, and plant variety, among other factors, affect spatial distribution of animals (Poole 1974, Taylor 1984). The preliminary nature of the Robinson et al. (1978)

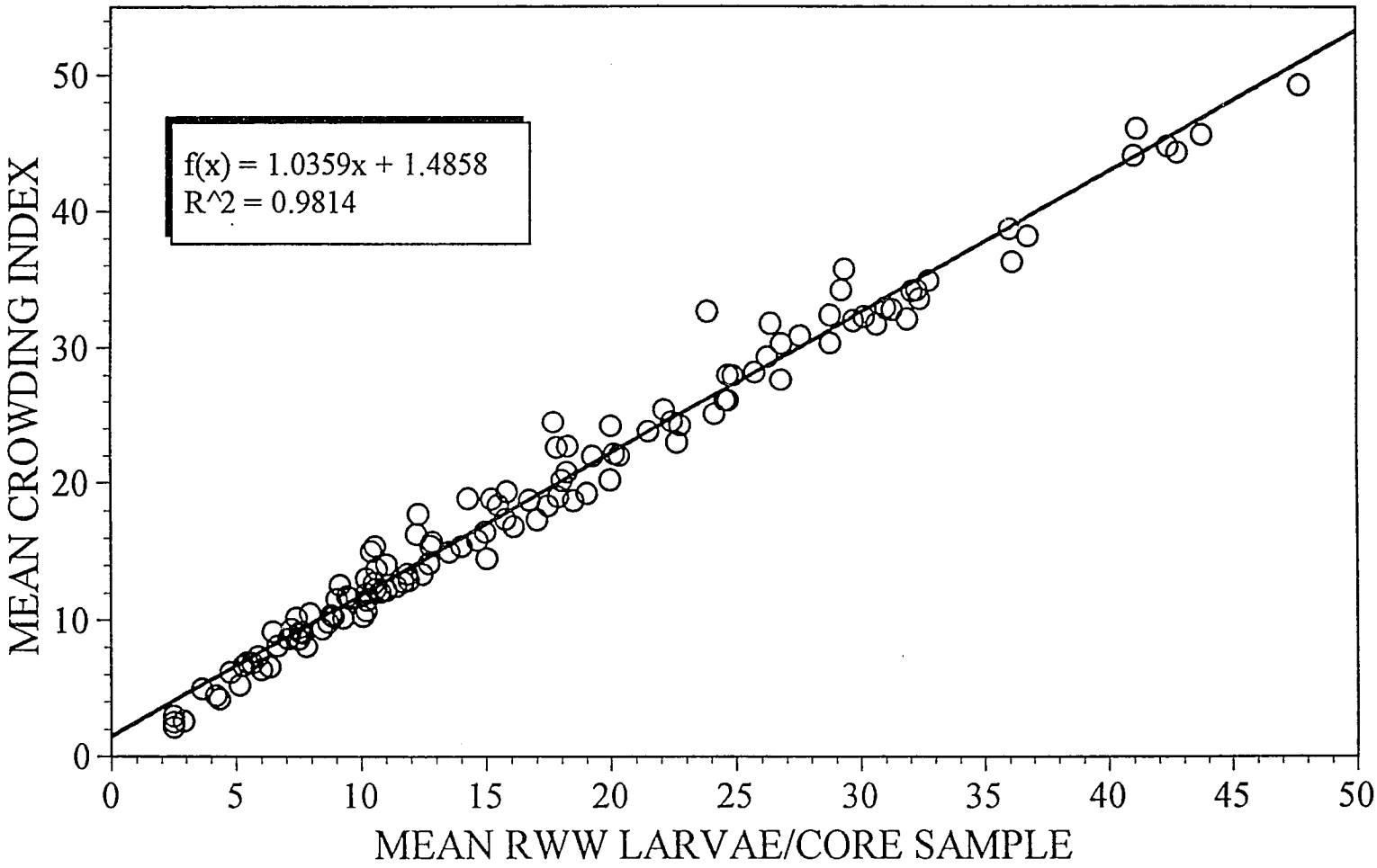

Figure 1.3. Iwao's patchiness regression for total RWW larvae over all collection dates in 1993 and 1994.

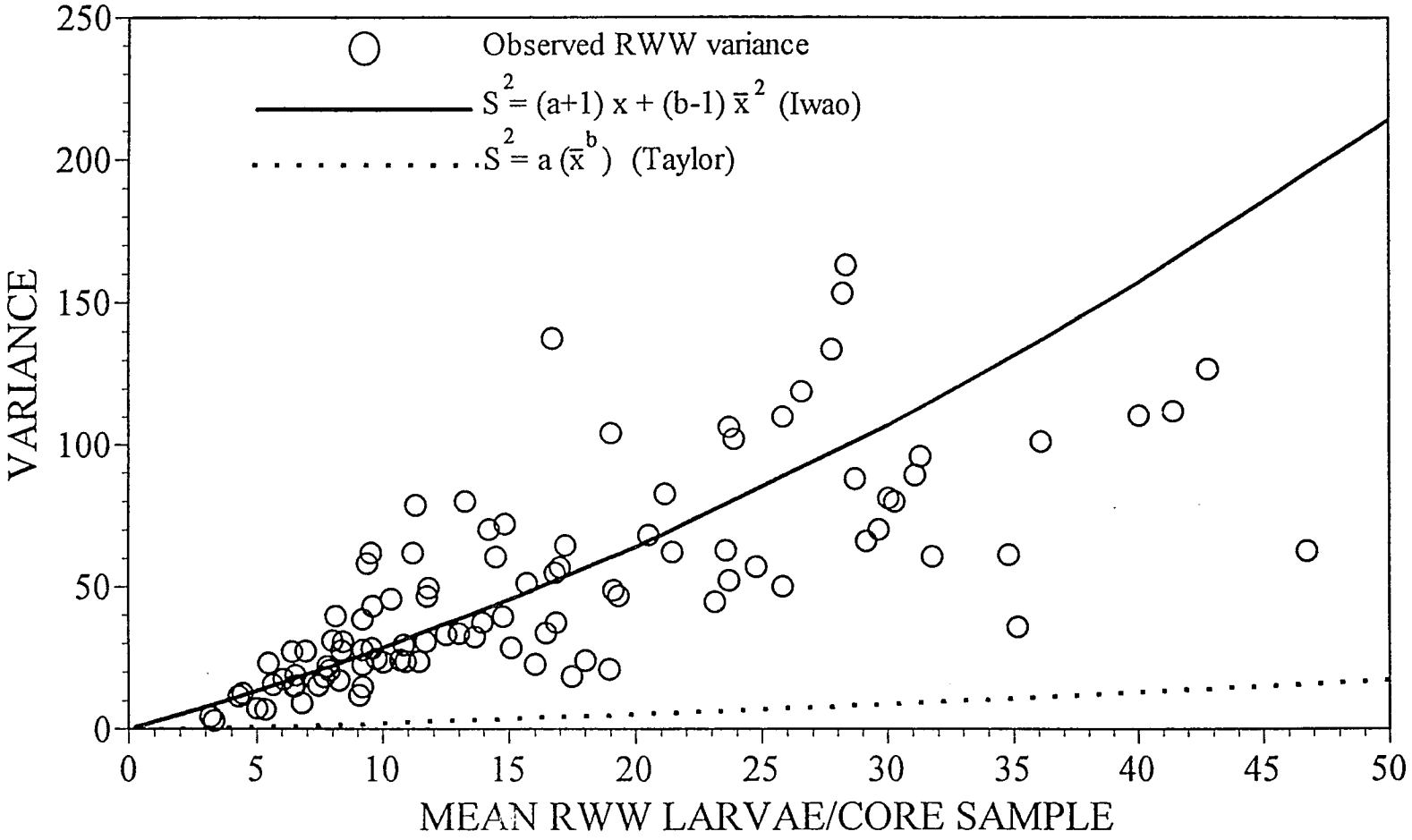

Figure 1.4. Comparison of predicted variance estimates as a function of mean density for Taylor's power law and Iwao's patchiness regression with the computed RWW variances for total RWW over all collection dates in 1993 and 1994.

study makes full explanation of the differences difficult. The k_c determined from our data also indicates that RWW populations followed a near random distribution. A k_c was not reported by Robinson et al. (1978).

The values for the aggregation indices b and β, from Taylor's power law and Iwao's patchiness regression, respectively, indicate that RWW larval populations followed a near random distribution regardless of RWW population densities or sample dates. Cave et al. (1984) reported that Iwao's and Taylor's aggregation parameters b and β were significantly different from the Poisson slope of one, suggesting that RWW larvale populations were slightly clumped. These differences likely result from differences in plant density between the two studies. Plant densities in Cave et al. (1984) studies were1/0.1m^2. Plant densities in the present study were ca. 20/0.1m^2, the density recommended for commercial rice production in Louisiana (Anonymous 1987). Differences in sample number between the two studies could also contribute to the observed differences in aggregation indices. Plant density and distribution can have a significant influence on insect population density and spatial structure (Southwood 1989, Bach 1980).

Analysis of our data suggests that Iwao's patchiness regression model fits RWW larval distribution better than Taylor's power law model. In fact, the fit of Taylor's power law to larval distribution is so poor as to preclude its use for development of realistic larval sampling plans. The data also fit the negative binomial distribution well, and a k_c did exist. Results from this study suggest that aggregation

parameters from both Iwao's patchiness regression and the negative binomial models could be used to develop accurate and more efficient sampling plans for RWW larvae. Results of this study are however, limited to drill-seeded rice production. Other methods of rice production (i.e. water-seeding) are quite different from drill-seeded rice production practices (Anonymous 1987). The differences between these rice production methods may influence the spatial distribution exhibited by RWW larval populations. Additional research is needed to address these questions.

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CHAPTER II

SEQUENTIAL SAMPLING PLANS FOR RICE WATER WEEVIL, *Lissorhoptrus oryzophilus* KUSCHEL (COLEOPTERA: CURCULIONIDAE), LARVAE IN LOUISIANA

Introduction

Numerous insect pests occurring in the United States can cause significant yield loss in rice (Smith et al. 1986). The rice water weevil (RWW), *Lissorhoptrus oryzophilus* Kuschel, is the most economically important of these, causing significant damage in most rice growing areas of the United States (Way 1990). Adult RWW feed on rice leaf epidermal tissue, leaving narrow longitudinal scars (Newell 1913, Douglas & Ingram 1942). However, economic damage is associated with larval feeding, which occurs on rice roots (Way et al. 1991). Root feeding by RWW larvae can cause lodging, yellowing, stunting, and reduced yield (Bowling 1967). Yield losses resulting from RWW larval feeding range from 10 to 50% in Louisiana (Smith et al. 1986, USDA 1989).

Methods for efficiently and accurately monitoring pest populations are central to integrated pest management (IPM) theory (Nyrop & Binns 1991). Two methods are recommended for making RWW management decisions in Louisiana: indirect estimation of RWW larval density based on adult leaf feeding scars, and direct estimation based on larval sampling (Smith et al. 1986). Although intrinsically less time consuming, estimating larval density based on adult leaf feeding scars is not as accurate as larval sampling, and is useful only for crude estimates of larval density (Tugwell & Stephen 1981, Morgan et al. 1989). In fact, larval density based on leaf scar counts in Louisiana is usually confirmed by use of larval sampling (Smith et al. 1986). Sampling rice plants and surrounding soil for larvae provides accurate

estimates of larval density, but is time consuming and costly. Using current recommendations of 10 core samples/field for rice grown in Louisiana, we estimated that 40 to 50 minutes are required to sample a single field. In addition, early instar larvae are small and difficult to separate from other organisms and debris in the sample. Both methods used in Louisiana are based on fixed sample size: i.e. a fixed number of samples are required to estimate population size regardless of pest density. (Smith et al. 1986). These types of plans usually require greater sampling effort and are less cost effiecient than sequential sampling plans such as those based on sequential probability ratio tests (i.e. 2-SPRT, SPRT) (Nyrop & Binns 1991).

The number of samples required in sequential sampling plans varies with pest density. These plans generally reduce the number of samples needed to make pest management decisions compared to fixed precision level sample plans (Nyrop & Binns 1991). Consequently, sequential sampling plans have seen extensive use in pest management (Fowler & Lynch 1987a,b).

A sequential sampling plan based on adult feeding damage has been developed for RWW management in Arkansas (Tugwell & Stephen 1978, 1981). However, rice production practices and RWW biology differ sufficiently among rice producing states that methods used in one state may not be applicable in another. Cave et al. (1984) developed a sequential sampling plan for RWW larvae in Louisiana based on Green's fixed precision sequential sampling plan (Green 1970). However, the objective of their study was to aid in the identification of RWW resistant rice lines, and was not

developed under conditions used in commericial rice production. This plan may therefore not be useful for making RWW management for commercially grown rice in Louisiana. Rice water weevil larvae in drill-seeded rice were reported to be nearly randomly distributed (Chapter I). Thus, it should be possible to develop an accurate and reliable sequential sampling plan for RWW in Louisiana. The objective of this study was to develop and evaluate three sampling plans for RWW larvae in drill-seeded rice in Louisiana.

Materials and Methods

Parameters necessary for developing the SPRT (Wald 1945) and 2-SPRT (Mulekar et al. 1993) (sequential probability ratio test), and Kuno's (Kuno 1969) fixed precision sequential sampling plan were obtained from Chapter I. Decision limits, operating characteristics curves (OC) and average sample number curves (ASN) for the sequential probability ratio tests were developed following procedures of Fowler and Lynch (1987b) and Mulekar et. al. (1993), respectively. Decision limits for both SPRT's were constructed using 2 RWW larvae/core for the lower safety limit and the RWW economic threshold of 5 RWW larvae/core for the upper limit. Construction of upper and lower decision limits for both SPRT's were based on common k (k_c) of 13.63 (Chapter I), and type I and type II error rates of 0.10.

Performance of both SPRTs was tested using Monte Carlo simulation. Eleven values between 1 and 6 were selected to represent sample means. The range of these means includes the threshold for RWW larvae. The Statistical Analysis System (SAS

Institute Inc. 1991) subroutines **RANGAM** and **RANPOI** were used to generate the eleven means from the negative binomial distribution using k_c=13.63. The SPRT and 2-SPRT were used to make the treatment decision at each of the eleven sample means. One thousand iterations were performed at each of eleven sample means. Decision results were compiled and used to produce the OC and ASN curves.

The performance of Kuno's fixed precision sequential sampling plan was also evaluated using Monte Carlo simulation. The parameters α and β from Iwao's patchiness regression (Iwao 1968) were used to construct the stop lines for Kuno's fixed precision level sequential sampling plan. Values for α and β were obtained from Chapter I. Kuno's fixed precision sequential sampling plan was developed following the procedures of Hutchison et al (1988). Stop lines were developed to estimate RWW larvae density at the economic threshold of 5 larvae/core using precision levels of D=0.20 and 0.30. Random integers (mean=5, k_c=13.63) from the negative binomial distribution were selected until cumulative totals equaled or exceeded the computed stop lines. Simulations were performed 100 times, and results were summarized to produce actual precision levels, mean densities, and average sample numbers required to make a decision.

Results

Stop lines constructed for Kuno's sampling plan based on Iwao's regression parameters illustrate the relationship between mean RWW density and the required sample number (Fig. 2.1). Estimation of RWW economic threshold (5 larvae/core),

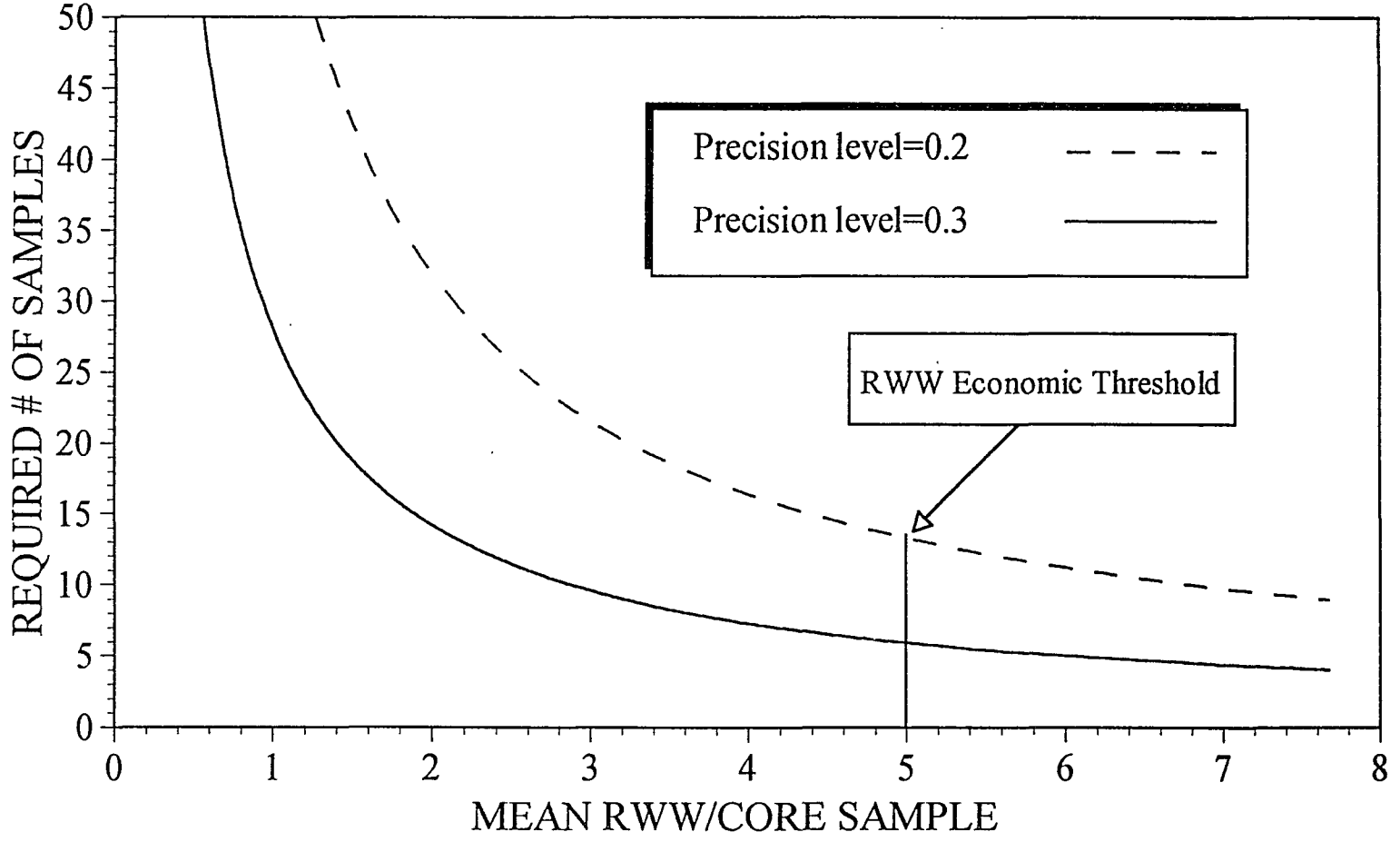

Figure 2.1. Relationship between RWW larva density/core sample and the required sample size at two precision levels for Kuno's fixed precision sequential sampling plan, based on 1993 and 1994 total RWW larvae.

based on Kuno's sampling plan, would require approximately 14 and 6 samples at the precision levels of D=0.20 and 0.30, respectively.

Rice water weevil threshold simulation results produced substantially lower variability at the tested precision levels than expected (Figs. 2.2, 2.3). Mean precision levels actually achieved were D=0.14 and D=0.19 at the specified precision levels of D=0.20 and D=0.30, respectively. Sample size at D=0.20 ranged from 9 to 20 with 84% of the values between 12 and 16, and at D=0.30 from 3 to 10 with 93% of the values between 4 and 8 (Fig. 2.4, 2.5). Mean density at D=0.20 ranged from 3.5 to 7.8 with 82% of the values between 4.4 and 6.0, and at D=0.30 from 3.2 to 10.0 with 62% of the values between 4.4 and 6.0 (Fig 2.6, 2.7). Sampling plans using Kuno's procedures were developed for both precision levels (Table 2.1). Average sample number curves produced by Monte Carlo simulation indicated that the 2-SPRT required fewer samples to make management decisions at all but the lowest tested larval mean density (Fig. 2.8). The greatest difference in the average number of samples required to make a management decision occurred in the 2.5 to 4.0 mean density range. The 2-SPRT and SPRT require an average of 2.43 and 2.59 samples, respectively, to make a management decision at RWW larva economic threshold (5 larvae/core sample). Operating characteristics curves generated by Monte Carlo simulation illustrate the probability of accepting the hypothesis (H1) that the field does not need to be treated at a specified mean density (Fig. 2.9). The operating characteristics curves for both SPRTs were similar. Observed Type I error rates

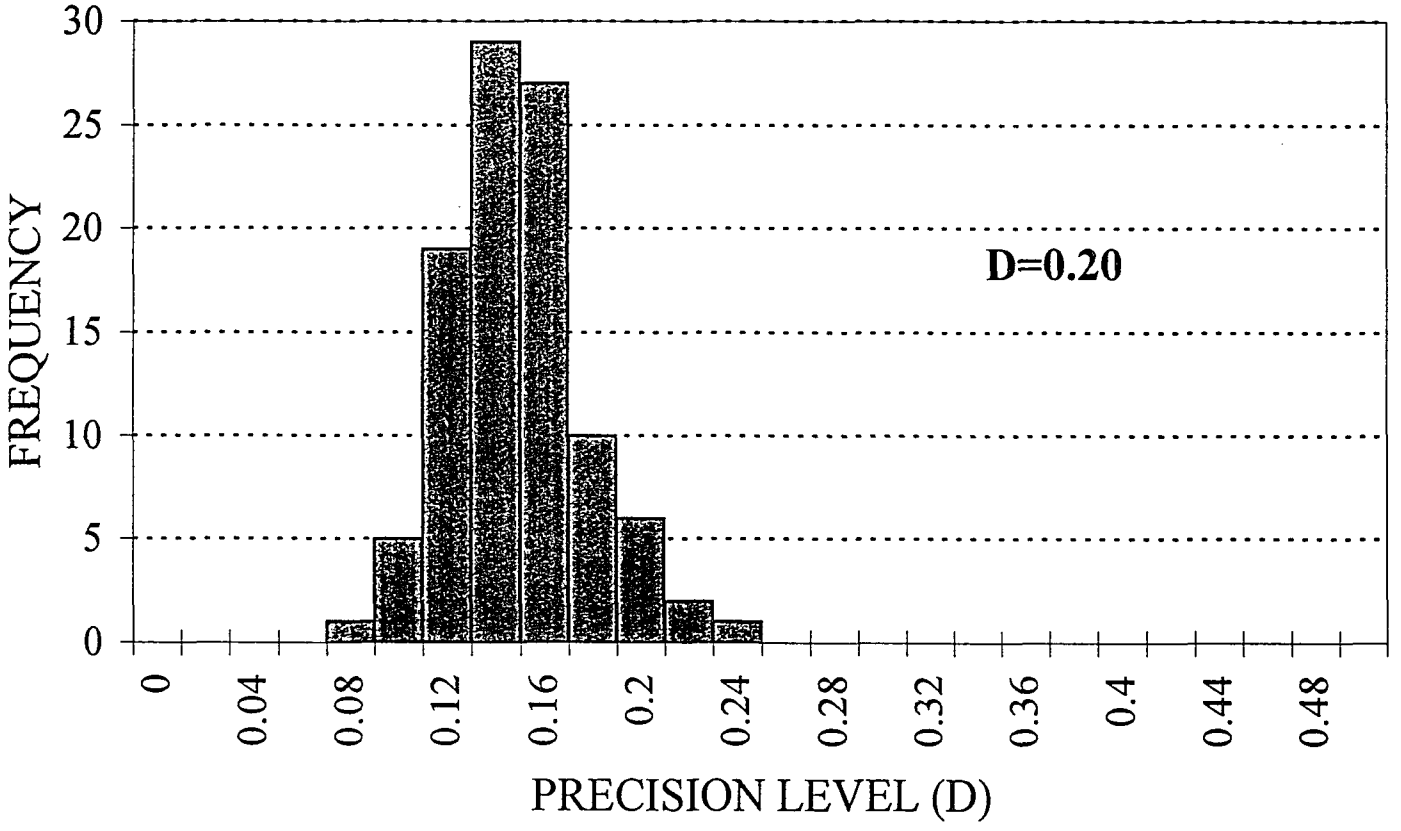

Figure. 2.2. Frequency distribution of precision level variability for Kuno's fixed precision sequential sampling plan at D=0.20 for total RWW larvae in 1993 and 1994.

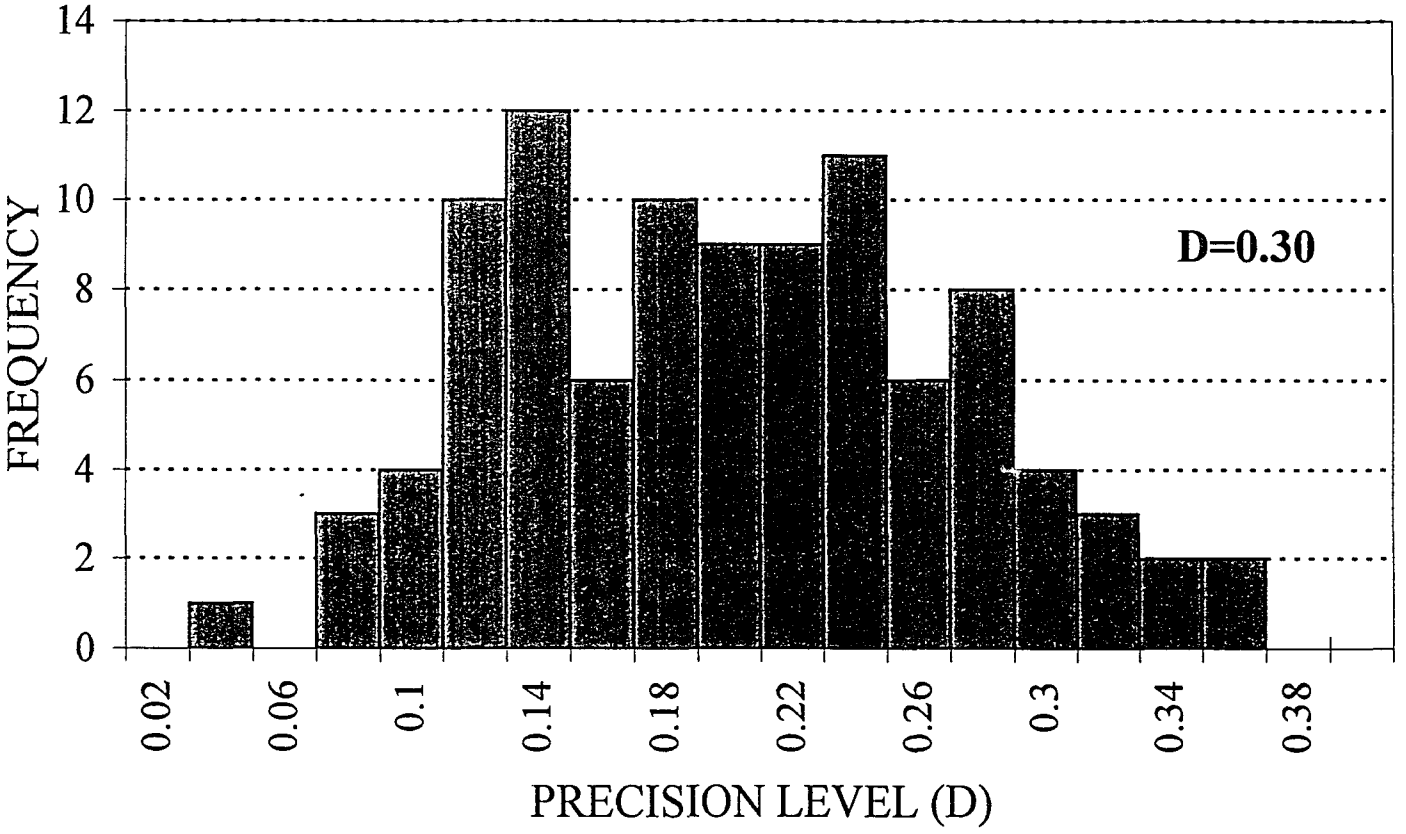

Figure 2.3. Frequency distribution of precision level variability for Kuno's fixed precision sequential sampling plan at D=0.30 for total RWW larvae in 1993 and 1994.

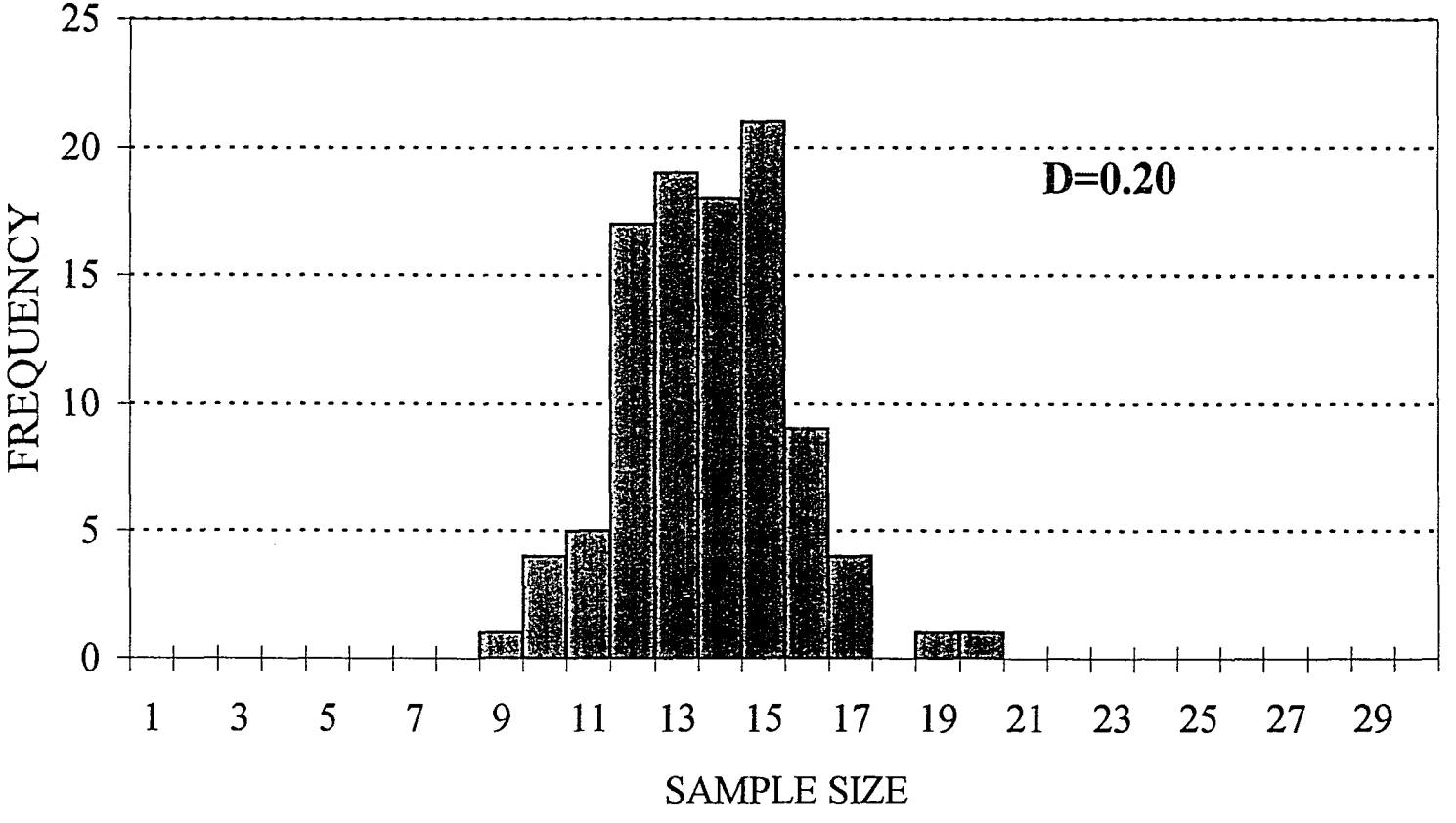

Figure 2.4. Frequency distribution of sample number variability for Kuno's fixed precision sequential sampling plan at D=0.20 for total RWW larvae in 1993 and 1994.

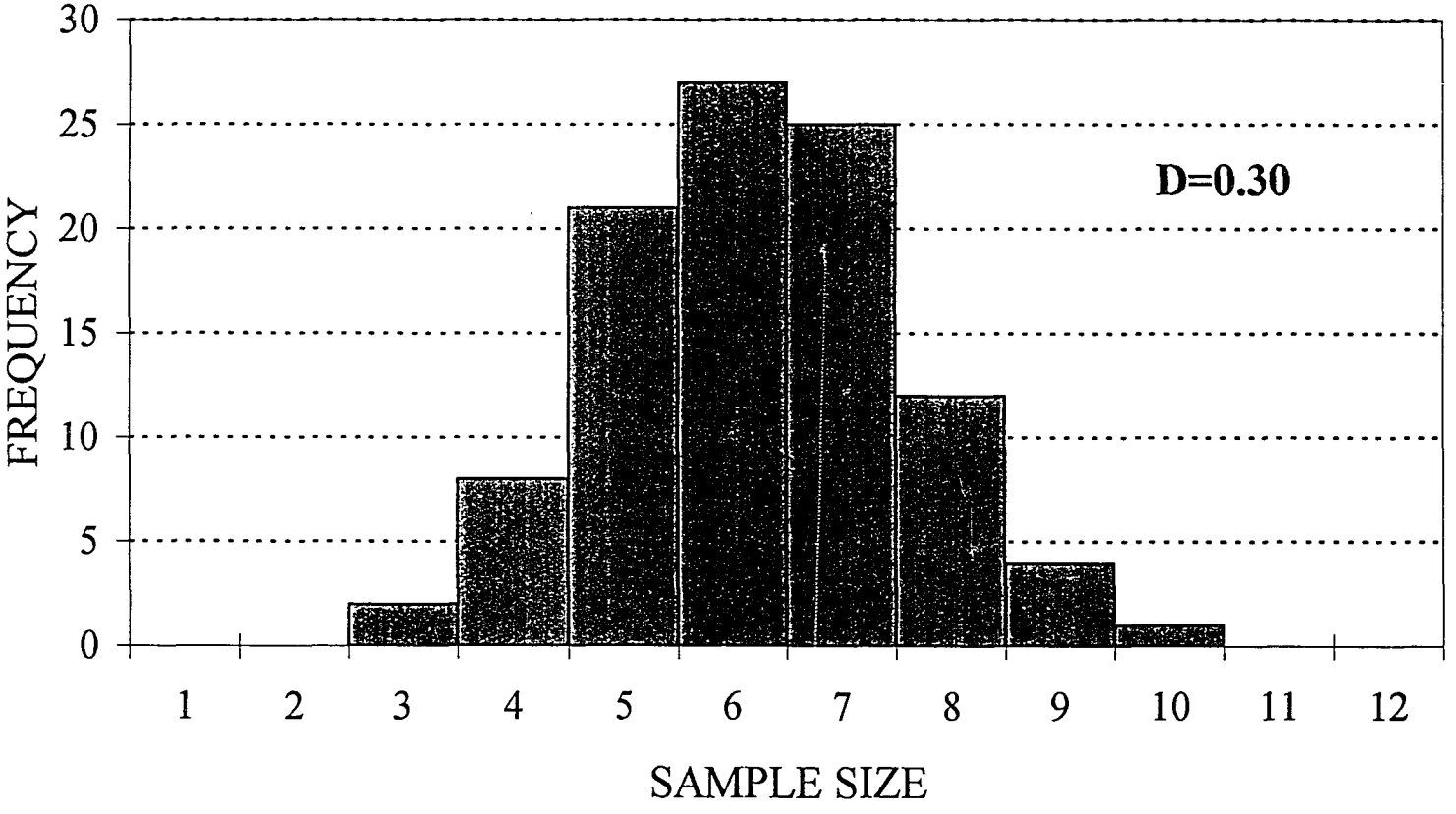

Figure 2.5. Frequency distribution of sample number variability for Kuno's fixed precision sequential sampling plan at D=0.30 for total RWW larvae in 1993 and 1994.

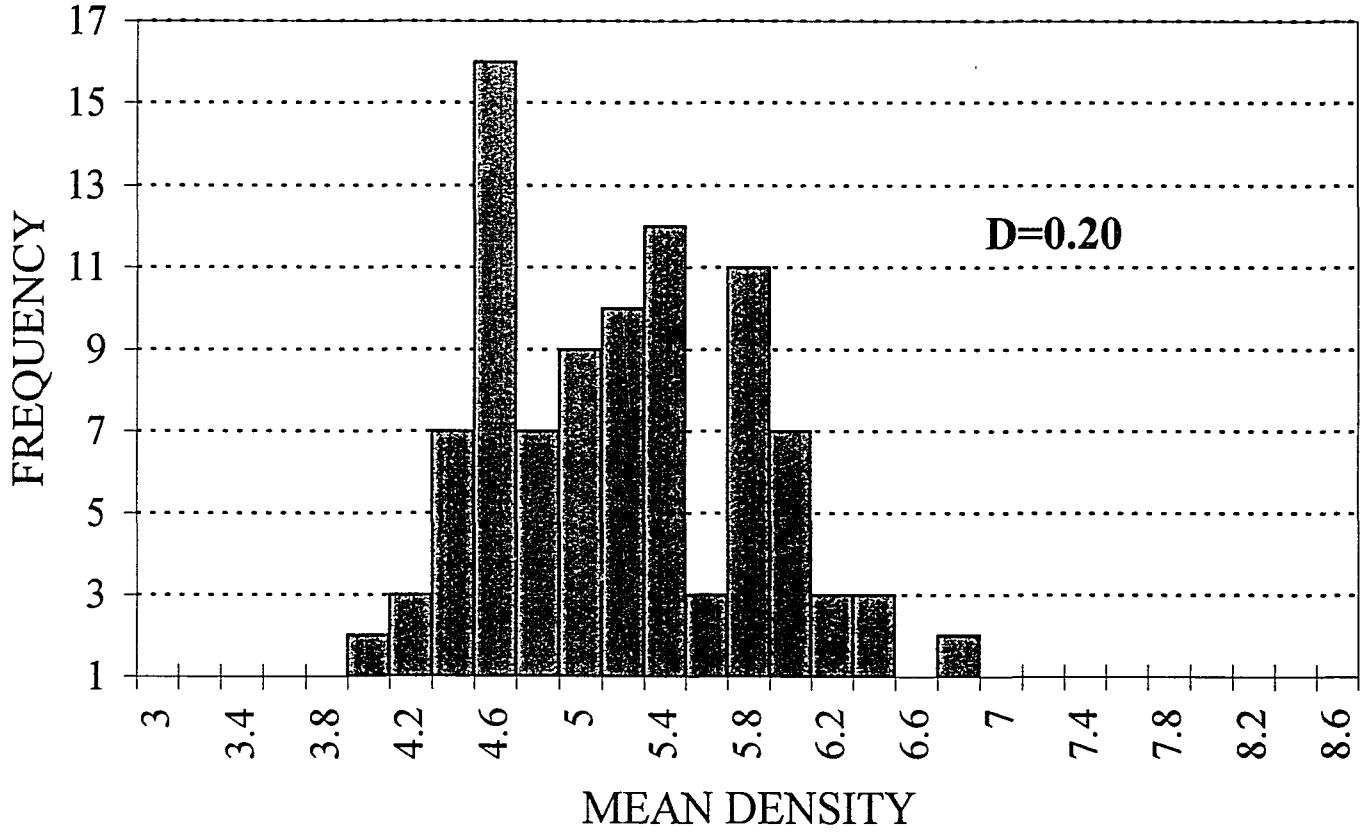

Figure 2.6. Frequency distribution of mean density variabiligy for Kuno's fixed precision sequential sampling plan at D=0.20 for total RWW larvae in 1993 and 1994.

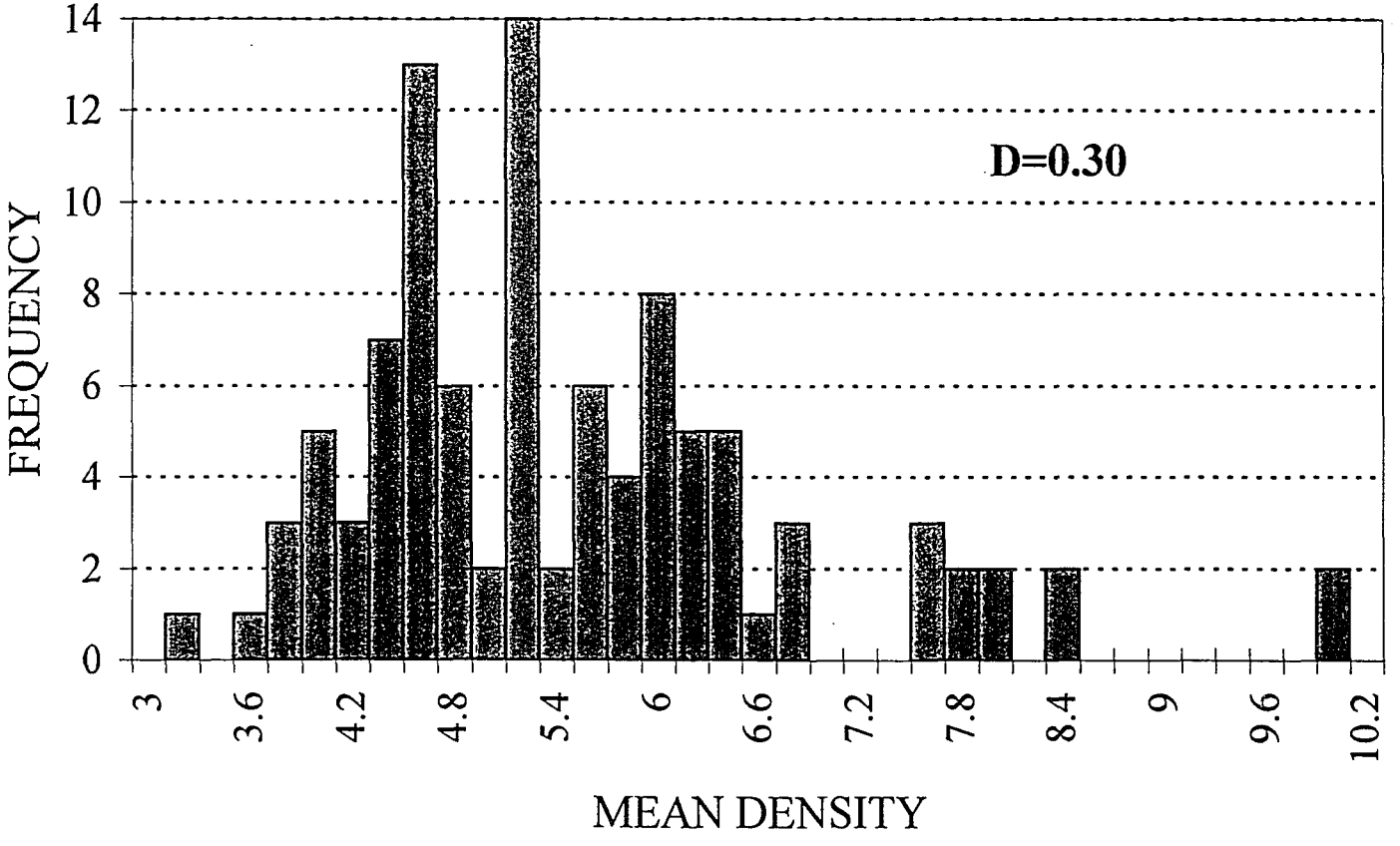

Figure 2.7. Frequency distribution of mean density variability for Kuno's fixed precision sequential sampling plan at D=0.30 for total RWW larvae in 1993 and 1994.

Table 2.1. Stop-line sampling plan for estimating RWW larva densities in drill-seeded rice in Louisiana at the observed precision level of D ≅ 0.14 and D ≅ 0.20 for Kuno's procedure.

Cumlative RWW larvae needed to stop sampling		Cumulative no. of core samples	
Observed Precision		Observed Precision	
D=0.14	D=0.20	D=0.14	D=0.20
113	35	2	2
89	32	3	3
80	31	4	4
76	30	5	5
73	30	6	6
71	29	7	7
70	29	8	8
69	29	9	9
68	29	10	10
68	29	11	11
67	29	12	12
67	28	13	13
66	28	14	14
66	28	15	15
66	28	16	16
66	28	17	17
65	28	18	18
65	28	19	19
65	28	20	20
65	28	21	21
65	28	22	22
65	28	23	23
65	28	24	24
64	28	25	25
64	28	26	26
64	28	27	27
64	28	28	28
64		29	

(Table con'd)

64	30	51
64	31	
64	32	
64	33	
64	34	
64	35	
64	36	
64	37	
64	38	
64	39	
64	40	
63	45	
63	50	
63	55	
63	60	

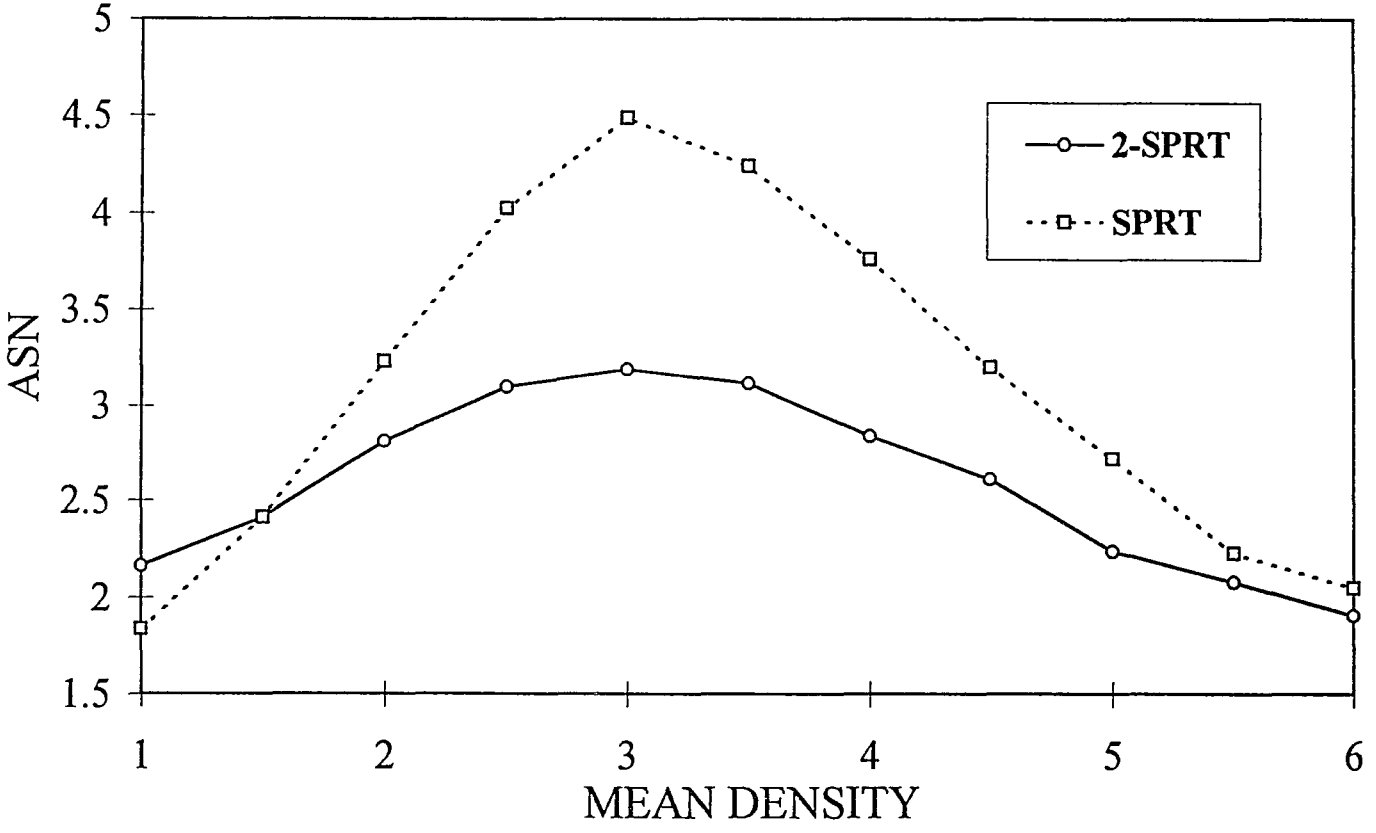

Figure 2.8. Average sample number curve (ASN) based on simulation results for total RWW larvae in 1993 and 1994.

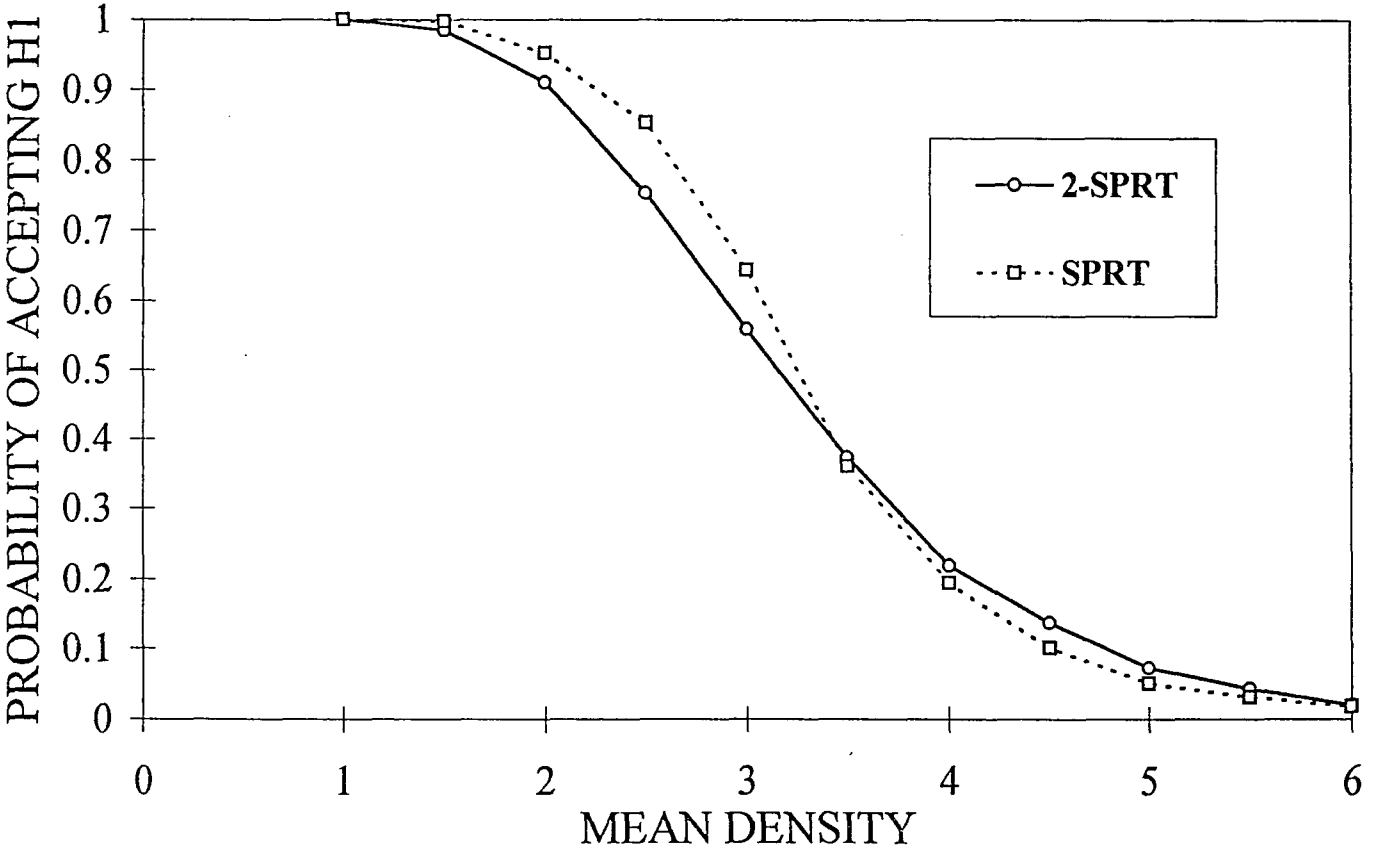

Figure 2.9. Operating characteristics curve based on simulation results for total RWW larvae in 1993 and 1994.

(applying control measures when none were needed) for the SPRT and 2-SPRT were 0.099 and 0.133, respectively. Observed Type II error rates (not applying control measures when they are needed) were 0.051 and 0.106 for the SPRT and 2-SPRT, respectively. Sampling plans computed for both SPRTs are presented in Figure 2.10 and Table 2.2.

Discussion

Monte Carlo simulations provided actual precision levels (D=0.14 and 0.19), when estimating RWW larva economic threshold, that were higher than those specified for the simulation (D=0.20 and 0.30). This would result in higher than necessary sampling effort at the selected precision levels. The conservative nature of Kuno's fixed precision sequential sampling plan has been reported by Hutchison et al. (1988), who found that Kuno's fixed precision sampling plan, when tested via computer simulation, maintained greater precision than the tested precision level regardless of *Acyrthosiphon pisum* (Harris) population densities and precision levels tested. Our results concur with theirs in that actual precision obtained from simulation results increased regardless of the precision level tested. Further, simulation analysis revealed that precision increased less dramatically at the highest (D=0.20) compared to the lowest (D=0.30) tested precision level. The sampling effort required to estimate RWW larva threshold density at the specified precision levels of D=0.20 and 0.30 were ≈14 and 6 soil core samples, respectively. The number of core samples needed to estimate RWW larva threshold density at the specified precision level of D=0.20 is greater than the current recommendation of 10

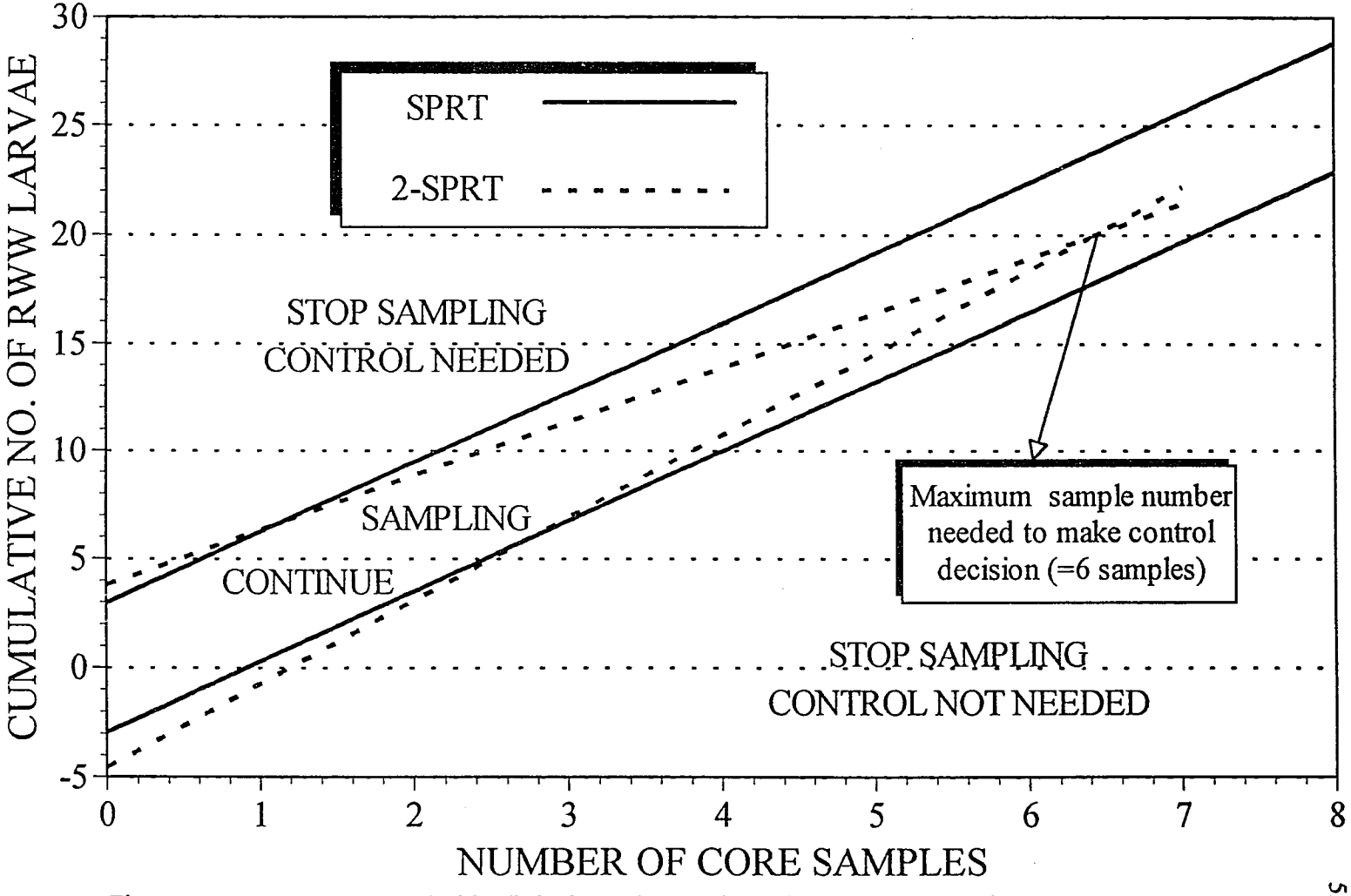

Figure 2.10. SPRT & 2-SPRT decision limits for total RWW larvae in 1993 and 1994 using common K=13.63.

Table 2.2. 2-SPRT and SPRT decision limits for RWW larvae in drill-seeded rice in Louisiana based on common k=13.63.

Cumulative no. of core samples	Cumlative RWW larvae needed to stop sampling			
	Upper Limit		Lower Limit	
	2-SPRT	SPRT	2-SPRT	SPRT
1	6.3	6.2	-0.8	0.3
2	8.8	9.4	3.1	3.5
3	11.3	12.7	7.1	6.7
4	13.8	15.9	11.1	9.9
5	16.3	19.1	15.1	13.2
6	18.6	22.4	18.6	16.4
7		25.6		19.6
8		28.8		22.9
9		32.1		26.1
10		35.3		29.3
11		38.5		32.6
12		41.7		35.8
13		44.9		39.1
14		48.2		42.3
15		51.4		45.5
16		54.7		48.7
17		57.9		51.9
18		61.1		55.2
19		64.3		58.4
20		67.6		61.6
21		70.8		64.9
22		74.1		68.1
23		77.3		71.3
24		80.5		74.6
25		83.7		77.8
26		86.9		81.1
27		90.2		84.2
28		93.4		87.5
29		96.6		90.7
30		99.9		93.9

(Table con'd)

*For 2-SPRT at core sample # 6. If cumulative total (CT)>18.6, stop sampling, control needed, if CT<18.6, stop sampling, control not needed. For SPRT at core sampl # 30. If CT>96.9, stop sampling, control needed. If CT<96.9, stop sampling, control not needed.

soil core samples (Smith et al. 1986) and would be of little benefit in a RWW IPM program. At the specified precision level of D=0.30 a 40% decrease in sampling effort is obtained over current sampling recommendations and an actual precision level of 0.19 is maintained. Thus Kuno's fixed precision sequential sampling plan at the specified precision level of D=0.30 could be useful in a RWW IPM program.

Sampling plans based on the two SPRTs are presented in Figure 2.10. Comparison of the decision lines illustrates the disparity between these two sequential sampling plans. Simulation analysis of the SPRT's revealed that the 2-SPRT generally required fewer samples to make terminating decisions for RWW management compared to the SPRT. Our results agree with Mulekar et al. (1993) who demonstrated that the 2-SPRT required substantially fewer samples to make terminating decisions for management of *Pseudatomoscelis seriatus* (Reuter) in cotton. This difference occurs primarily because of the convergent 2-SPRT decision limits (Figure 2.10).

Only the SPRT maintained estimated Type I and II error rates below the specified error rate of 0.10 in our study. The Type II error rate for the 2-SPRT was only marginally higher than the specified rate. Mulekar et al. (1993) reported that when tested at five k values and four specified error rates, estimated error rates were closer to the specified error rates for the 2-SPRT than for the SPRT. This was true only for the Type II estimated error rates in our simulation analysis.

The most important error type from a pest management viewpoint is the Type II error (probability of not applying control measures when control is needed). In our simulations the SPRT maintained the type II error rate below the specified level and less than half that of the 2-SPRT (0.051 vs. 0.106 respectively). However, the SPRT requires substantially more samples to make a management decision relative to the 2-SPRT (nearly twice as many as the 2-SPRT at moderate RWW larval density). This problem could be partially alleviated by reducing the specified error rate for the SPRT until estimated errors were comparable to the 2-SPRT. However, because the SPRT decision boundaries are parallel, sample number requirements would be more variable and thus would occasionally require greater sampling effort than the 2-SPRT (Mulekar et al. 1993).

Both classification (SPRTs) and estimation (Kuno's) sampling plans have been used extensively in integrated pest management systems (Fowler & Lynch 1988, Nyrop & Binns 1991, Binns & Nyrop 1992). However, estimation sampling plans generally require substantially greater sampling effort than classification sampling plans (Nyrop & Binns 1991, Binns & Nyrop 1992). Of the three sequential sampling plans tested in this study the 2-SPRT required the least sampling effort, while Kuno's fixed precision sequential sampling plan required the greatest. The effort required to take and process samples for RWW larvae are time consuming and costly. Thus, Kuno's plan would probably not be adopted for commercial use, but could be useful when accurate estimation of RWW larva density is necessary. Of the two SPRT's

tested, Wald's SPRT required greater sampling effort, but produced lower Type II error rates. Both SPRT procedures, however, performed reasonably well and could substantially decrease sampling effort compared to current RWW larva sampling programs employed to make RWW management decisions in Louisiana. Results of this study are however, limited to drill-seeded rice production. Other methods of rice production (i.e. water-seeding) are quite different from drill-seeded rice production practices (Anonymous 1987). The differences between these rice production methods may limit the sampling plans developed in this study to use in drill-seeded systems. Additional research is needed to address these questions.

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CHAPTER III

DESCRIBING RICE WATER WEEVIL, *Lissorhoptrus oryzophilus* KUSCHEL (COLEOPTERA: CURCULIONIDAE) SPATIAL DISPERSION PATTERNS USING SPATIAL AUTOCORRELATION ANALYSIS AND AGGREGATION INDICES

Introduction

The rice water weevil *Lissorhoptrus oryzophilus* Kuschel, is a serious pest of rice in many rice producing areas of the United States, Japan, Korea and Taiwan (Way 1990). Rice water weevil (RWW) adults and larvae attack rice (Way et al. 1991). Adults feed by chewing leaf epidermal tissue causing longitudinal scars in rice leaves (Smith 1983). Adult feeding may occasionally result in plant death under intense RWW pressure (Douglas & Ingram 1942). Isely and Schwardt (1934) reported that adult RWW feed on the forming rice grain. However, economic damage is generally associated with larval feeding (Bowling 1967, Smith 1983 & 1986, Way 1990, Way et al. 1991). Root feeding by larvae causes plant stunting, lodging, stand reduction, prolonged development, and yield reduction (Bowling 1967, Smith 1983, Smith et al. 1986, USDA 1989). Yield losses of 10 to 50% have been reported in Louisiana (Smith 1983, USDA 1989). In Louisiana there is a 45 kg/Ha reduction in rice grain for every larva found in a 10 cm sample (Way et al. 1991).

Development of accurate and efficient sampling programs require knowledge of the pest species' spatial distribution (Binns & Nyrop 1992, Nyrop & Binns 1991). Traditional statistical methods that incorporate variance-mean relationships have been used to described RWW spatial distributions (Robinson et. al. 1978, Tugwell & Stephen 1981, Cave & Smith 1984). Spatial distribution of RWW feeding scars in rice fields was described by Tugwell and Stephen (1981) using k from the negative binomial distribution. The variance/mean ratio (Taylor 1984), Taylor's power law

(Taylor 1961), and Iwao's patchiness regression (Iwao 1968) have been used to describe spatial patterns of RWW larvae (Robinson et. al. 1978, Cave & Smith 1984,). Spatial distributions of RWW adults, eggs, and pupae; however, have not been described.

Traditional statistical methods have proven valuable for estimating population parameters (mean and variance) and for the development of insect-pest sampling plans (Southwood 1989, Binns & Nyrop 1992). However, when using these methods information on the relative position of individual values in a data set is lost. This positional information is essential for evaluating underlying processes determining spatial dispersion patterns of organisms (Williams et. al. 1992). Because spatial autocorrelation techniques are not dependent on the variance-mean relationship, spatial autocorrelation may be useful in validating traditional methods for determining spatial distributions of animals, and may also lead to a better understanding of processes determining animal spatial distributions. A variable can be said to be autocorrelated when the value of a variable at one location can be predicted by knowing the values of the same variable at other locations (Legendre & Fortin 1989). The objectives of this study were to describe the spatial dispersion patterns of RWW life stages using spatial autocorrelation analysis and compare the results of that analysis with the results of analyses using traditional statistical methods.

Materials and Methods

All research was conducted during 1994 at the Rice Research Station, near Crowley, Louisiana. The rice cultivar "Lemont" was drill-seeded to a field measuring 24.4 x 7.5 m on 9 April 1994. Rice was planted at 112 kg/ha with 17.5 cm row spacing. Thirty-five cm alleys were placed longitudinally every 1.22 m to facilitate data collection. Nitrogen (13:13:13 N-P-K) was pre-plant incorporated at 50.6 kg/ha then broadcast pre-flood at 101.2 kg/ha (21:0:0 N-P-K). Propanil was applied pre-flood at 3.4 kg AI/ha for weed control. A stratified sampling scheme was employed by dividing the field into 400 0.37 m^2 quadrates.

Rice water weevil adults were sampled (one sample /quadrate) from each of 400 quadrates by encompassing a randomly selected 0.073 m^2 area with a floating circular tube, and counting adult weevils observed in 30 seconds. Adults were collected as they were counted so as not to count the same individual twice. Adults were released into the same quadrate from which they were collected, when counting for each quadrate was completed. Rice water weevil adults generally seek shelter as daytime temperatures increase and are consequently more difficult to find from late morning to early evening. Because sampling for adults required 2-4 hours, counts of adult RWW may have been higher when sampling began than at the completion of the sample period. Therefore, sampling was conducted during early morning hours and quadrates were sampled in random sequence. Adult sampling began one day post-flood and continued at one week intervals for five consecutive weeks.

Rice water weevil eggs, larvae and pupae were sampled weekly (2 June-30 June 1994) beginning one week after permanent flood. A single randomly selected soil/plant sample was taken from each quadrate using a 10.2 x 10.2 (ht. x dia.) cm core sampler. Each sample was placed into a plastic bag, taken to a RWW extraction shed, and soil washed from plants into a 60 mesh screen sieve. Collected larvae and pupae were floated in a saturated NaCl solution, removed, and placed into labeled scintillation vials filled with 70% EtOH. Vials with larvae and pupae were taken to the laboratory where they were sorted by life stage according to head capsule size (Cave & Smith 1981) and counted. Plant samples were labeled, and returned to their plastic bag (to reduce desiccation). Bagged plant samples were placed into a cooler, taken to the laboratory and stored at 4 °C until processing. Plant samples were processed by clipping the plant roots and leaves to within 2.5 and 13 cm of the plant base, respectively. Plant roots and leaves were clipped because adults lay eggs in the leaf sheath below the waterline, but above the plant base (Grigarick & Beards 1965). Clipped plants were labeled and stored in 70% EtOH until they could be examined for eggs. Storing plants in EtOH preserved the eggs and extracted chlorophyll from the plant stems and leaves making the eggs easier to find. Leaf sheaths were removed, microscopically examined, and RWW eggs counted. Egg sampling began one week post-flood and continued at one week intervals for three consecutive weeks.

Spatial and temporal distribution of RWW life stages was evaluated using k from the negative binomial distribution (Anscombe 1949), b from Taylor's power law

(Taylor 1961), β Iwao's patchiness regression (Iwao 1968), and spatial autocorrelation analysis (Sokal & Oden 1978a,b). Sample sums for non-transformed data were compared to the negative binomial and Poisson distributions using distribution fitting software (Bestfit®, 31 Decker Road; Newfield, NY 14867) and tested for goodness of fit using the χ^2 statistic. Maximum likelihood estimation of k was determined following procedures of Bliss and Fisher (1953).

Log transformation of Taylor's power law yields the linear equation:

$$\log s^2 = a + b \log \bar{x}$$

where s^2 = the sample variance; a = a scaling factor related to sample size; b = a species specific measure of aggregation; and $\bar{x}$ = the sample mean (Taylor 1961). Data were fitted to the log transformed model by regressing the log of the variance against the log of the mean.

Iwao's patchiness regression is given by the equation: $\dot{x} = \alpha + \beta m$, where α= an index of basic contagion; β = a density-contagioness coefficient; $\bar{x}$ = the population mean, and = Lloyd's (1967) mean crowing index. Iwao's patchiness regression parameters were determined by regressing Lloyd's mean crowding index on the sample mean. Lloyd's mean crowing index is expressed by the equation:

$$\dot{x} = m + \left(s^2 / m - 1 \right)$$

where m = the sample mean; and s^2 = the sample variance.

The parameters k from the negative binomial distribution, b from Taylor's power law, and β from Iwao's patchiness regression are considered aggregation indices (Iwao 1968, Taylor 1961, 1984). The parameter k of the negative binomial distribution describes clumped ($0 \leq k \leq 8$) through more random ($8 \leq k \rightarrow \infty$) populations. The parameters b and β describe from near regular ($0 < b\ \beta < 1$), though random (b & $\beta = 1$) and increasing population aggregation ($1 < b\ \beta \rightarrow \infty$) (Southwood 1989).

Spatial dependence of the data was determined by spatial autocorrelation analysis using a program written by B. E. Moser (Department of Experimental Statistics, Louisiana State University, Baton Rouge, LA 70803) and run using the Statistical Analysis System (SAS Institute Inc. 1991). The spatial autocorrelation coefficient, Moran's I, was computed at each of nine distance classes, where each distance class represented 0.61 m. Values of Moran's I range from $\approx +1$ to -1, with expected values under the null hypothesis of no spatial dependence ≈ 0, and significant positive and negative values indicating similarity and dissimilarity of variable values at given distance classes, respectively. Distance classes were evaluated based on orthogonal and diagonal connections (Sokal & Oden 1978a).

Correlograms were constructed by plotting the autocorrelation coefficients for each distance class against each distance class. Global tests of spatial dependence were performed on each correlogram using Bonnferroni's approximation (Oden

1984). Correlograms were constructed for RWW adults, eggs, larvae, and pupae. Sample time intervals were chosen so as to follow a single RWW generation.

Results

Peak density for adults, eggs, larvae, and pupae occurred 1, 1, 3, and 5 wks after permanent flood, respectively (Table 3.1). These results indicate that initial movement of adults into the field and subsequent oviposition may have been missed. Decreasing the time between sample intervals may be necessary to increase spatial and temporal resolution of RWW dispersion patterns in the initial stages of the RWW life cycle.

Values of k varied considerably across sample dates and RWW life stages (Tables 3.2-5). Regardless of sample date or life stage RWW populations did not significantly differ from the negative binomial distribution (Tables 3.2-5). Coefficients of determination from Taylor's power law indicated that less than 40% of the variation in egg and larva means was explained by regressing the log of the variance against the log of the mean for all sample dates except eggs collected on June 16 and larvae collected on June 30. Fitting the data to Taylor's power law yielded statistically significant regressions for all RWW life stages on all sample dates (Tables 3.2-5). All regression slopes were significantly greater than zero, however, none were significantly different from one ($P \leq 0.05$), indicating that RWW data followed a Poisson distribution (Tables 3.3-4). The poor fit of the data to this model may limit the use of Taylor's power law for the development of egg and larva sampling plans

Table 3.1. Mean density ± standard error for RWW developmental stages in 1994.

Weeks Post-Flood	Mean rice water weevil/sample ($\bar{x}$) ± SE			
	adults	eggs	larvae	pupae
0	0.18 ± 0.02	*	*	*
1	1.41 ± 0.07	16.08 ± 0.55	0.03 ± 0.01	0
2	1.34 ± 0.07	8.11 ± 0.27	10.11 ± 0.30	0
3	0.72 ± 0.05	0.74 ± 0.06	29.06 ± 0.63	0.12 ± 0.02
4	0.53 ± 0.04	*	19.49 ± 0.48	4.14 ± 0.19
5	0.59 ± 0.04	*	7.28 ± 0.28	4.91 ± 0.22

1. Mean Rice water weevil density/sample.
2. * indicates samples were not taken at this sample period.

Table 3.2. Taylor's power law regression parameters (a, b), Iwaos patchiness regression parameters (α, β), k from the negative binomial distribution, and the coeffiecients of determination (r^2) for 1994 adult RWW collected by date.

Sample Date	a[1]	b[2]	$r^{2(3)}$	α[1]	β[2]	$r^{2(4)}$	k[5]
May 25	-0.003	1.123	0.839*	-0.140	1.130	0.883*	1.88
June 1	-0.081	1.377	0.740*	-0.279	1.186	0.905*	11.39
June 8	-0.061	1.311	0.592*	-0.566	1.312	0.763*	9.56
June 15	-0.191	1.634	0.510*	0.340	0.838	0.700*	5.07
June 22	0.033	0.873	0.642*	0.178	0.903	0.799*	11.80
June 29	-0.045	1.333	0.655*	-0.352	1.263	0.758*	7.14

1. Intercepts were not significantly different from zero ($P \leq 0.05$).
2. Slopes were not significantly different from the Poisson slope of one (T-test; $P \leq 0.05$).
3. * indicates a significant regression of log variance against log mean for Taylor's power law ($P \leq 0.05$).
4. * indicates a significant regression of Lloyds mean crowding index against the mean for Iwao's patchiness regression ($P \leq 0.05$).
5. * indicates data significantly deviates from negative binomial distribution ($P \leq 0.05$).

Table 3.3. Taylor's power law regression parameters (a, b), Iwaos patchiness regression parameters (α, β), k from the negative binomial distribution, and the coeffiecients of determination (r^2) for 1994 RWW eggs collected by date.

Sample Date	a[1]	b[2]	$r^{2(3)}$	α[1]	β[2]	$r^{2(4)}$	k[5]
June 2	0.661	1.128	0.304*	4.557	1.081	0.705*	26.65
June 9	0.078	1.422	0.371*	0.327	1.208	0.722*	30.48
June 16	-0.077	1.794	0.774*	-0.876*	1.690	0.832*	6.07

1. Intercepts were not significantly different from zero ($P \leq 0.05$).
2. Slopes were not significantly different from the Poisson slope of one (T-test; $P \leq 0.05$).
3. * indicates a significant regression of log variance against log mean for Taylor's power law ($P \leq 0.05$).
4. * indicates a significant regression of Lloyds mean crowding index against the mean for Iwao's patchiness regression ($P \leq 0.05$).
5. * indicates data significantly deviates from negative binomial distribution ($P \leq 0.05$).

Table 3.4. Taylor's power law regression parameters (a, b), Iwaos patchiness regression parameters (α, β), k from the negative binomial distribution, and the coeffiecients of determination (r^2) for 1994 RWW larvae collected by date.

Sample Date	a[1]	b[2]	$r^{2(3)}$	α[1]	β[2]	$r^{2(4)}$	k[5]
June 9	0.289	1.184	0.241	1.541	1.062	0.737	29.77
June 16	0.630	0.910	0.295	3.023*	0.979	0.974	13.02
June 23	0.479	1.002	0.238	2.426	0.998	0.919	11.62
June 30	-0.191	1.634	0.666	0.029	1.192	0.911	7.93

1. Intercepts were not significantly different from zero ($\underline{P} \leq 0.05$).
2. Slopes were not significantly different from the Poisson slope of one (T-test; $\underline{P} \leq 0.05$).
3. * indicates a significant regression of log variance against log mean for Taylor's power law ($\underline{P} \leq 0.05$).
4. * indicates a significant regression of Lloyds mean crowding index against the mean for Iwao's patchiness regression ($\underline{P} \leq 0.05$).
5. * indicates data significantly deviates from negative binomial distribution ($\underline{P} \leq 0.05$).

Table 3.5. Taylor's power law regression parameters (a, b), Iwaos patchiness regression parameters (α, β), k from the negative binomial distribution, and the coeffiecients of determination (r^2) for 1994 RWW pupae collected by date.

Sample Date	a[1]	b[2]	$r^{2(3)}$	α[1]	β[2]	$r^{2(4)}$	k[5]
June 16	-0.036*	2.249	0.779*	-1.765*	2.641	0.784*	3.35
June 23	-0.632*	2.449	0.645*	-1.917	1.704	0.761*	15.85
June 30	-0.240	1.885	0.642*	-0.876	1.485	0.771*	11.32

1. Intercepts were not significantly different from zero ($\underline{P} \leq 0.05$).
2. Slopes were not significantly different from the Poisson slope of one (T-test; $\underline{P} \leq 0.05$).
3. * indicates a significant regression of log variance against log mean for Taylor's power law ($\underline{P} \leq 0.05$).
4. * indicates a significant regression of Lloyds mean crowding index against the mean for Iwao's patchiness regression ($\underline{P} \leq 0.05$).
5. * indicates data significantly deviates from negative binomial distribution ($\underline{P} \leq 0.05$).

for RWW. Iwao's patchiness regression modeled all RWW life stages well relative to Taylor's power law, accounting for greater than 70% of the sample variance on all sample dates (Tables 3.2-5). The values obtained for the aggregation index; "β" of Iwao's patchiness regression were not significantly different from the Poisson slope of one ($P \leq 0.05$), indicating, in agreement with Taylor's power law that all RWW life stages were nearly randomly distributed on all sample dates. Values of k provided results similar to those of Taylor's power law and Iwao's patchiness regression except RWW eggs tended to be near random in distribution initially, becoming weakly clumped over time. Adults and pupae were clumped initially, becoming nearly random over time.

Correlograms indicated that RWW adults, eggs, larvae, and pupae exhibited significant spatial dependence on all of the sample dates (Figures 3.1-5). Spatial density maps generally supported these results (Figure 3.6-10). Spatial correlograms constructed for RWW adults were globally significant for diagonal connections on June 1, and orthogonal connections on June 8, 15, and 22 (Bonferroni's approximation $\alpha'=0.0055$) (Figure 3.1-2). These results indicate that significant spatial structure was present only for those sample dates. Rice water weevil adults collected on June 1 showed significant high order negative autocorrelation based on diagonal connections. These results could be explained by the presence of a density gradient, and appears to be supported by the surface density map, which shows a distinct southeasterly density gradient (Figure 3.2). Significant low and high order

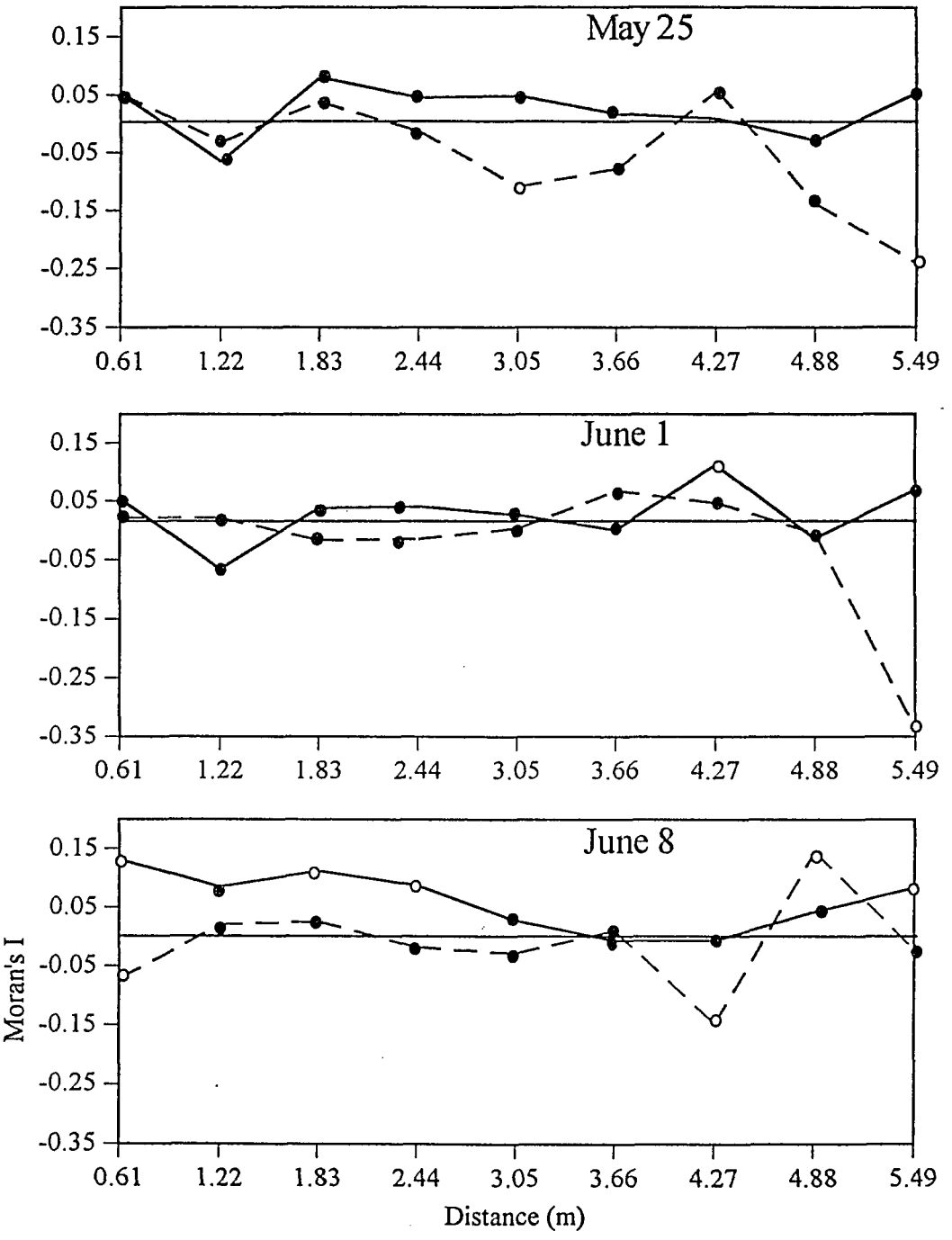

Figure 3.1. Spatial correlograms for adult Rice Water Weevil collected in 1994. Solid lines and dashed lines represent orthogonal and diagonal connections, respectively. Open circles represent significant autocorrelation coefficients ($P<0.05$).

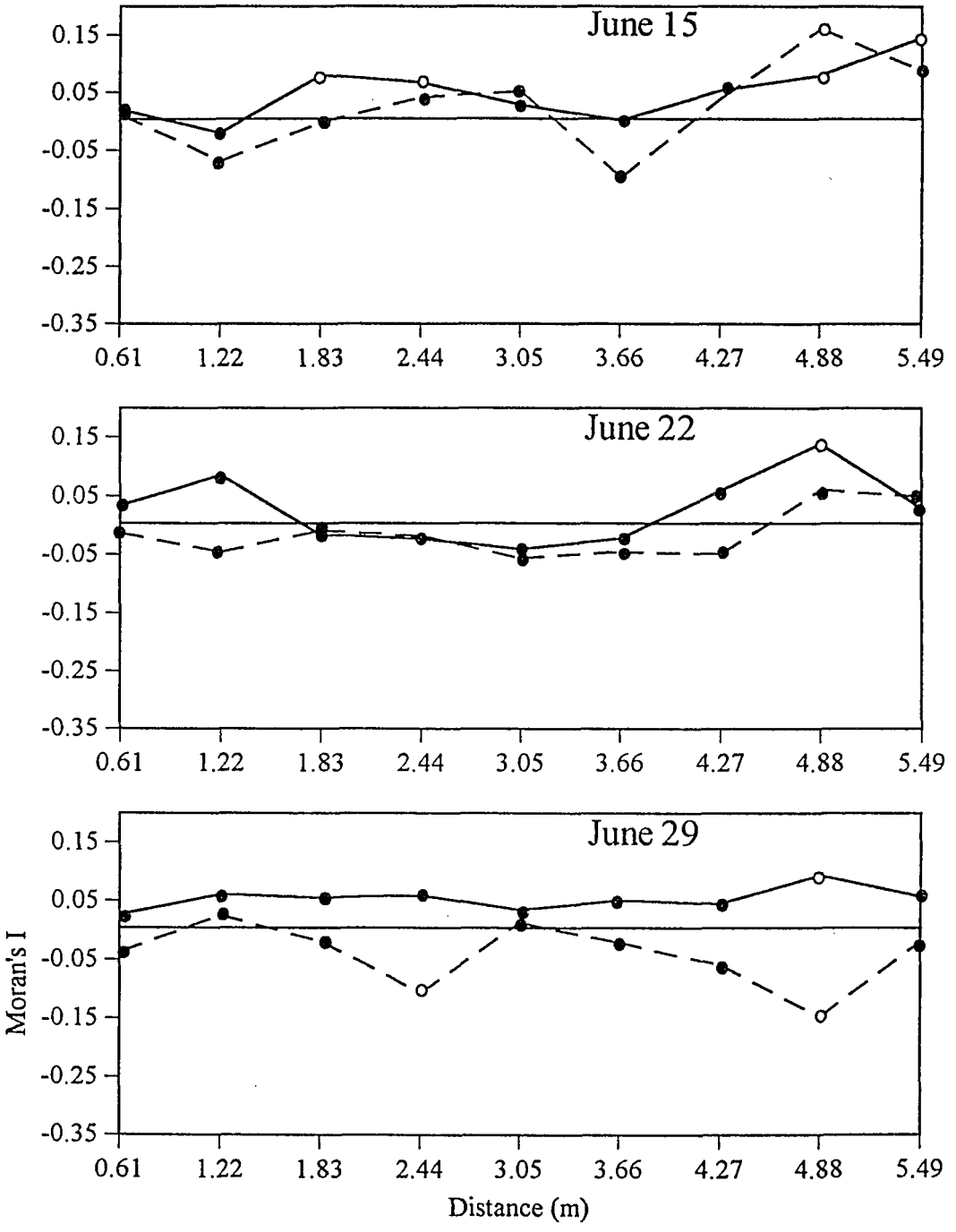

Figure 3.2. Spatial correlograms for adult Rice Water Weevil collected in 1994. Solid lines and dashed lines represent orthogonal and diagonal connections, respectively. Open circles represent significant autocorrelation coefficients ($P<0.05$).

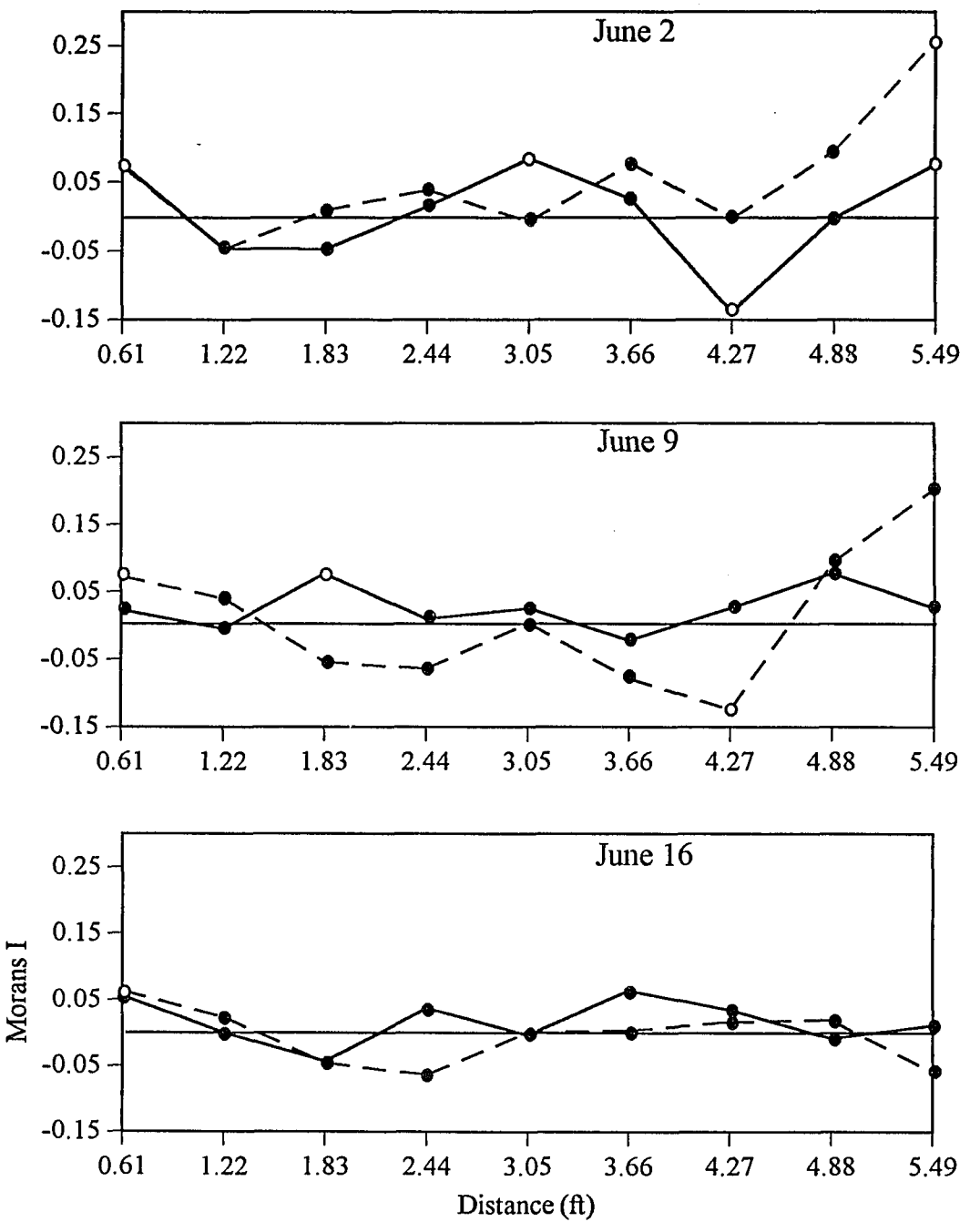

Figure 3.3. Spatial correlograms for RWW eggs collected in 1994. Solid lines and dashed lines represent orthogonal and diagonal connections, respectively. Open circles represent significant autocorrelation coefficients ($P<0.05$).

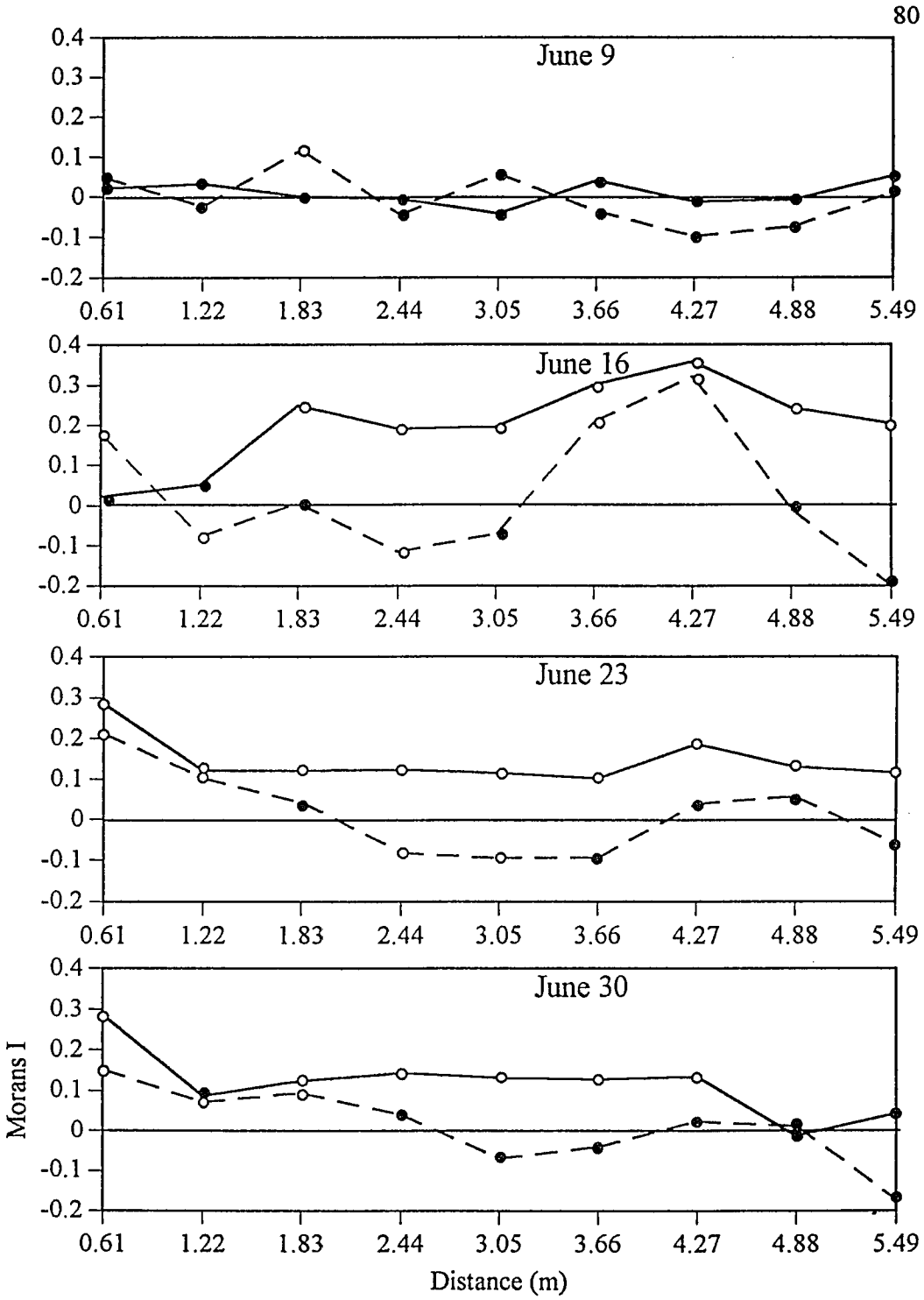

Figure 3.4. Spatial correlograms for RWW larvae collected in 1994. Solid lines and dashed lines represent orthogonal and diagonal connections, respectively. Open circles represent significant autocorrelation coefficients ($P<0.05$).

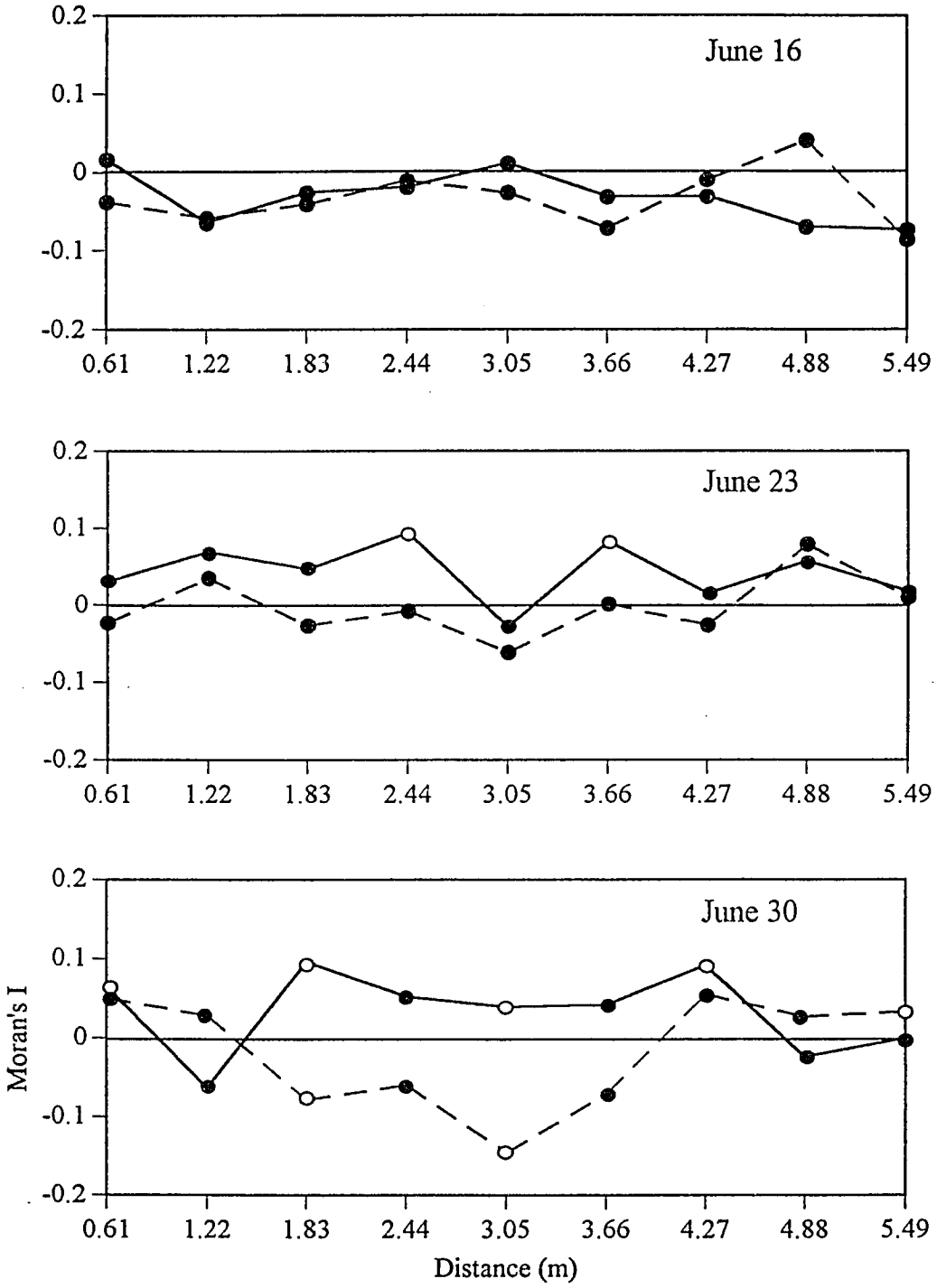

Figure 3.5. Spatial correlograms for RWW pupae in 1994. Solid lines and dashed lines represent orthogonal and diagonal connections, respectively. Open circles represent significant autocorrelation coefficients ($P<0.05$).

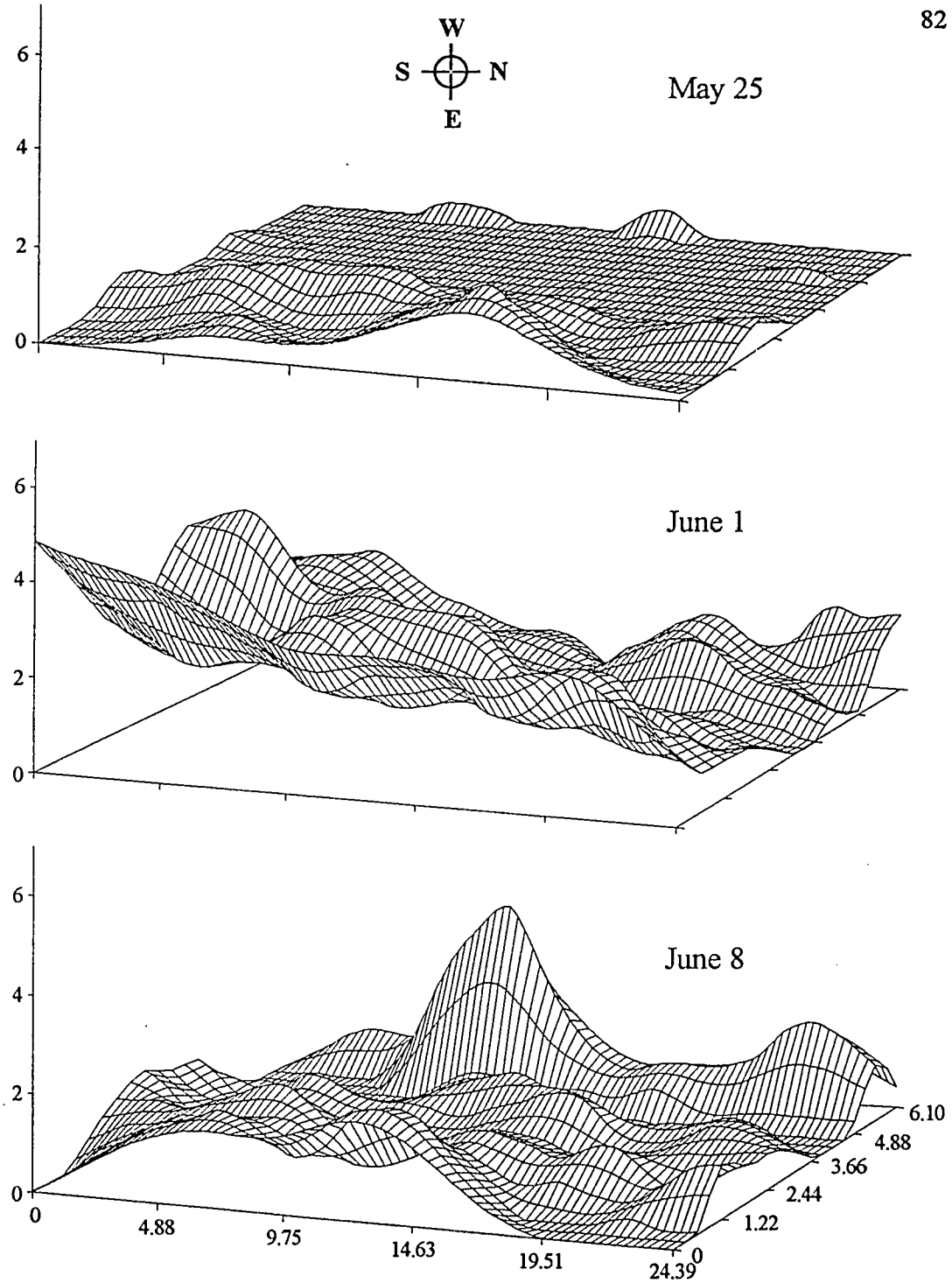

Figure 3.6. Spatial density maps for adult Rice Water Weevil collected in 1994. Axes z=Adult RWW density (adults/sample); x and y=distance in meters.

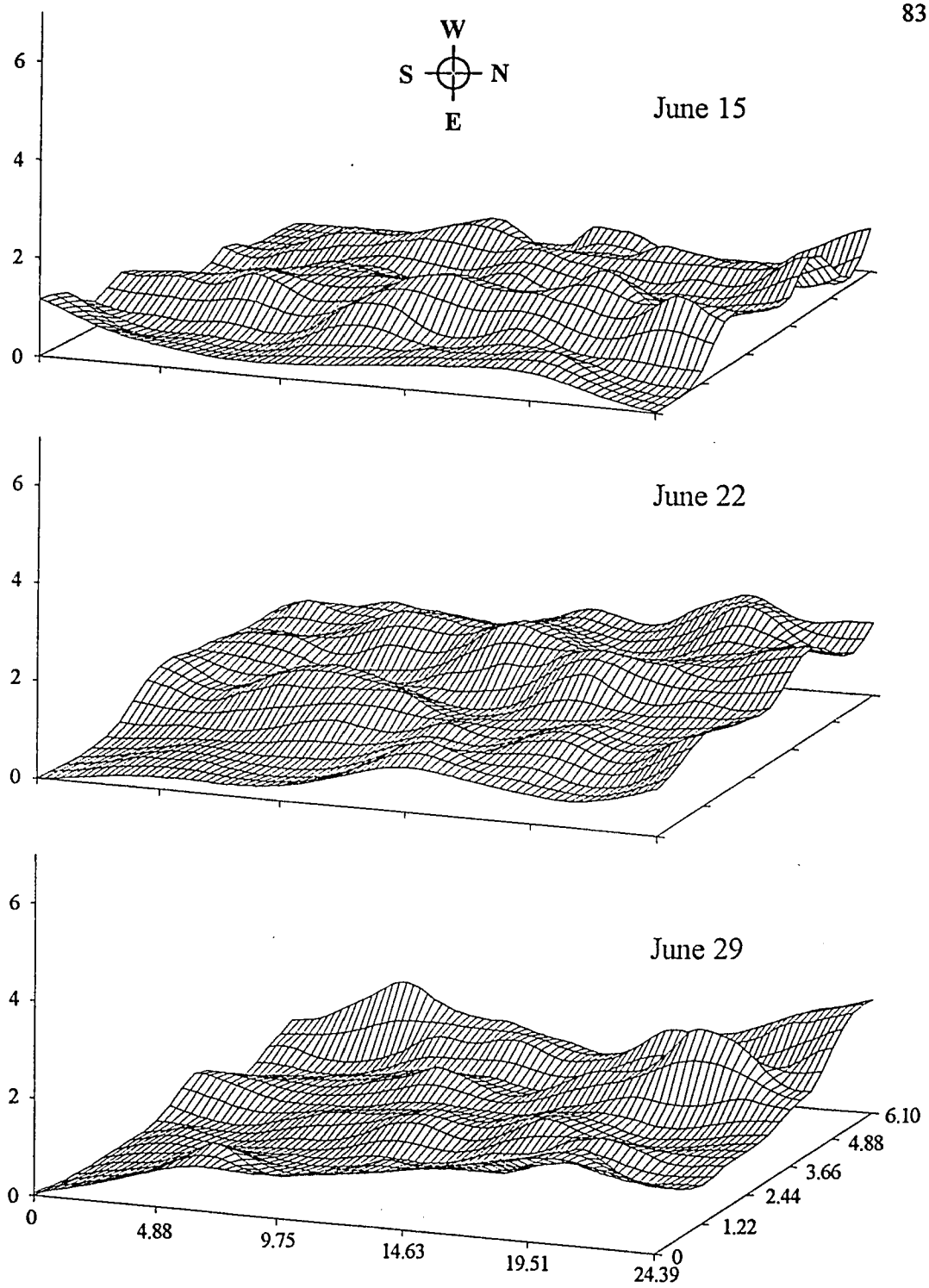

Figure 3.7. Spatial density maps for adult Rice Water Weevil collected in 1994. Axes z=Adult RWW density (adults/sample); x and y=distance in meters.

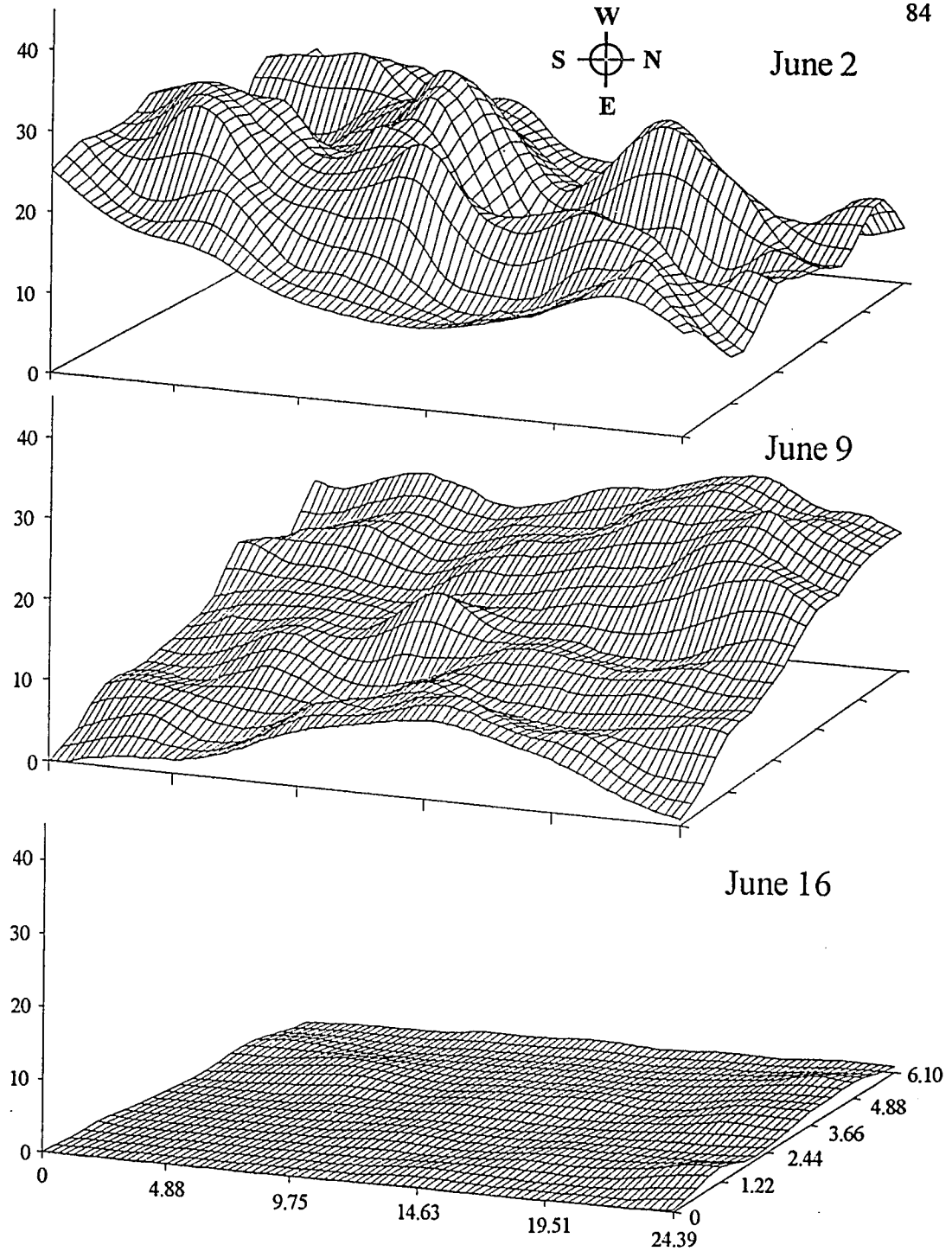

Figure. 3.8. Spatial density maps for Rice Water Weevil eggs collected in 1994. Axes z=RWW egg density (eggs/sample); x and y=distance in meters.

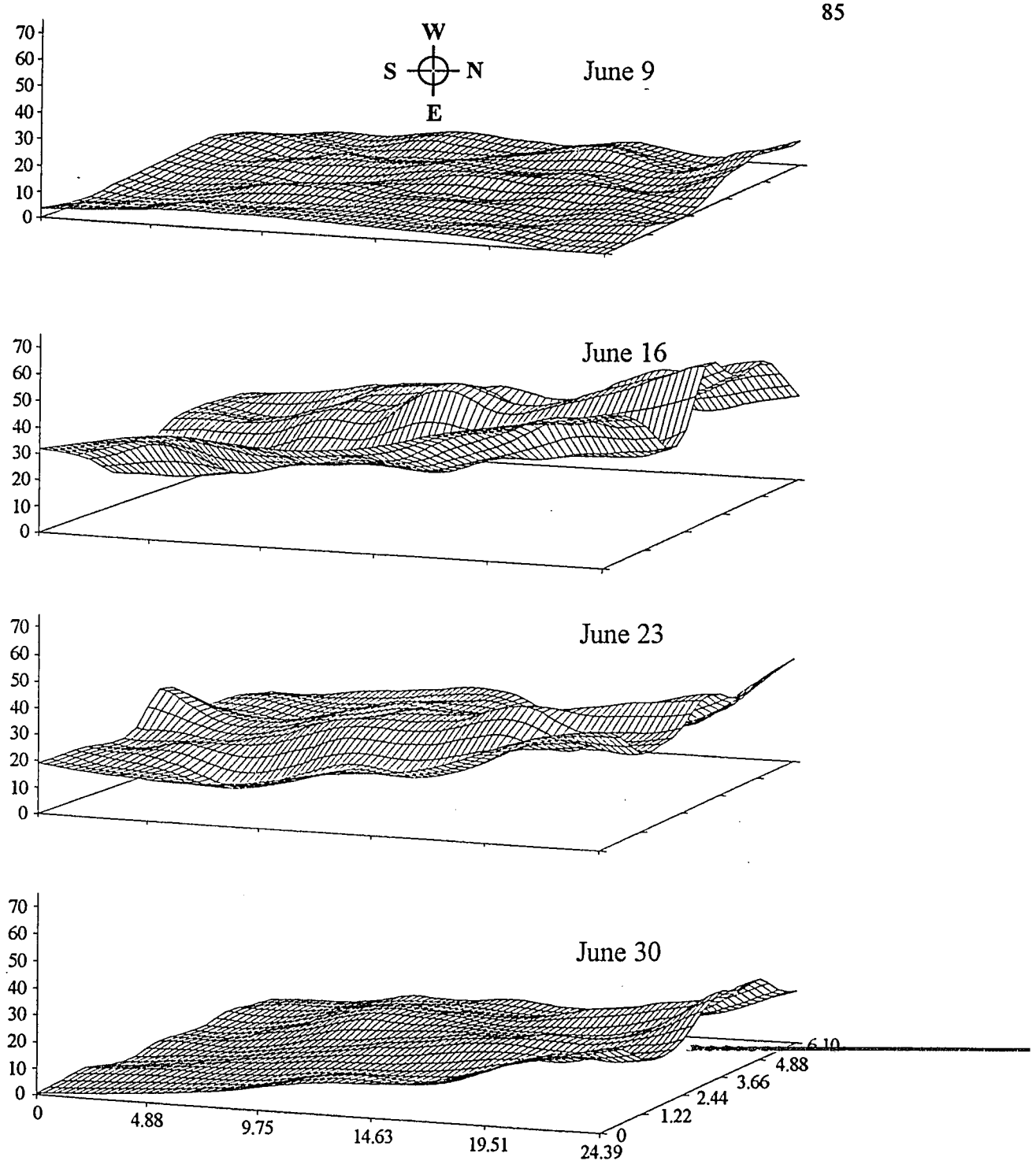

Figure 3.9. Spatial density maps for Rice Water Weevil larvae collected in 1994. Axes z=RWW larva density (larvae/sample); x and y=distance in meters.

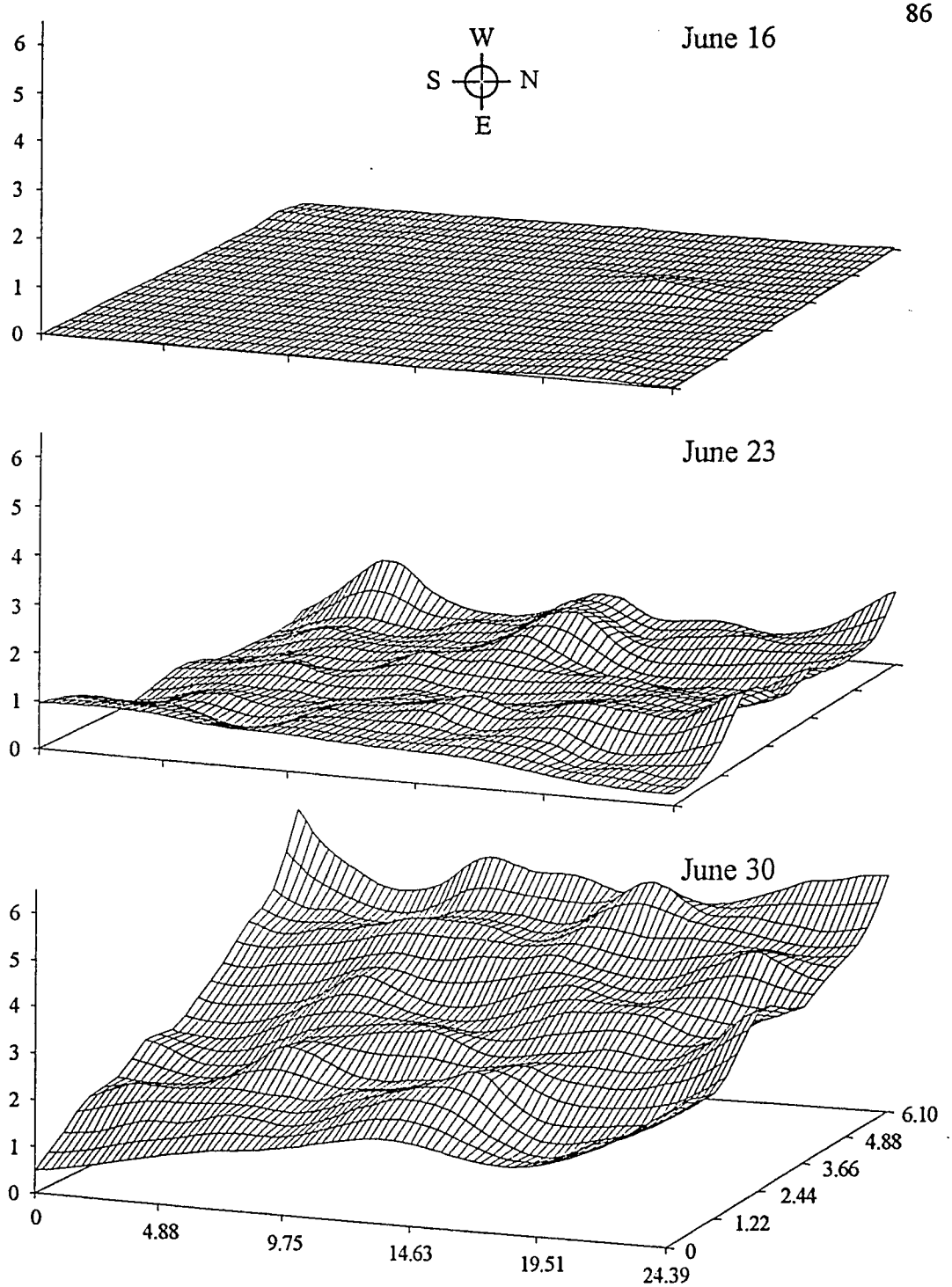

Figure. 3.10. Spatial density maps for Rice Water Weevil pupae collected in 1994. Axes z=RWW pupa density (pupae/sample); x and y=distance in meters.

positive correlations were found for adults collected on June 8 based on orthogonal connections (Figure 3.1). Significant positive correlations first turned zero at 3.7 m then became significantly positive again at 5.5 m. These results indicate the presence of patches about 13.7 m^2 regularly distributed in the sampling array. The surface area map supports this spatial structure (Figure 3.2). A similar spatial pattern was also found for adults collected on June 15, although patches appear to be less dense and smaller in size (Figure 3.4). A single high order positive correlation occurred for adults collected on June 22. This result may indicate a symmetric arrangement of patches within the sample area; however, no other correlations were significant, indicating the absence of spatial dependence at all other distances analyzed.

Spatial correlograms constructed for RWW eggs were globally significant only for the orthogonal connections for the June 2 sample period (Bonferroni's approximation α'=0.0055) (Figure 3.3). The spatial correlogram for this sample period indicates distinct patches of approximately 1.4 to 5.8 m^2 occurring regularly throughout the sample area (Figures 3.3 &3.8). This observation is supported by the presence of low order positive and negative correlations, and a high order positive correlation.

All correlograms constructed for RWW larva sample data were globally significant except the correlogram based on orthogonal connections for the June 9 sample date (Bonferroni's approximation α'=0.0055). Correlograms based on diagonal connections for the June 9 sample data exhibited one significant positive low

order correlation (Figure 3.4). This result suggests the occurrence of about 1.4 m^2 patches within the sampling array, and is supported by the spatial density map for this sample date (Figure 3.9). The correlogram based on diagonal connections for the June 16 sample date exhibit significant positive low and high order correlations, and significant negative low order correlations. The structure of this correlogram suggests that patches are more distinct and variable in size compared to patches that occur for the June 9 sample period. Correlograms for June 23 and 30 sample periods exhibit similar patterns to the June 16 sample period, although patch size becomes greater in diameter and less distinct, and a density gradient is apparent (Figure 3.7). These results are supported by the spatial density maps for these sample periods (Figure 3.8). Correlograms based on orthogonal connections for all other sample periods except June 9, exhibited significant low and high order positive autocorrelations only (Figure 3.7). These results suggest that larval density is similar at nearly all distance classes and contribute little to the elucidation of patch occurrence or size.

Correlograms constructed for RWW pupae were globally significant (Bonferroni's approximation $\alpha'=0.0055$) only for the last sample date of June 30 (Figure 3.9). Both low and high order significant positive and negative correlations were present based on diagonal connections ($P \leq 0.05$). Significant low order positive and negative correlations coupled with high order significant positive correlations indicate small patches (4 m^2 <) occurring regularly within the sample area. However,

the high order significant negative value suggests the presence of a density gradient. Both phenomenon are supported by the spatial density map (Figure 3.10). The correlogram for orthogonal connections also indicates small patches occurring in the sample area, but does not indicate the presence of a spatial gradient (Figure 3.9).

Discussion

Values of *k* by date indicate that RWW adults, eggs, larvae, and pupae were generally nearly randomly distributed. Values of *k* for RWW larvae reported by Robinson et al. (1978) were generally lower than those reported here, indicating a more clumped distribution than our data would suggest. Differences in *k* values observed between the two studies may be explained at least in part, by methodological differences between the studies. Sample unit size, mean density, and plant variety among other factors, affect spatial distribution of animals (Poole 1974, Taylor 1984).

The values for the aggregation indices *b* and β, from Taylor's power law and Iwao's patchiness regression, respectively, indicate that RWW populations were nearly randomly distributed regardless of population densities or sample dates. Cave et al. (1984) reported that Iwao's and Taylor's aggregation parameters *b* and β were significantly different from the Poisson slope of one, suggesting that RWW larvae populations were clumped. These differences likely resulted from differences in plant density between the two studies. However, the objective of their study was to develop a sampling plan to aid in the identification of RWW resistant rice lines, and

was not developed under conditions used in commercial rice production. Plant density in the Cave et al. (1984) study were 1/0.1m^2. Plant density in the present study was ca. 20/0.1m^2, the density recommended for commercial rice production in Louisiana (Anonymous 1987). Differences in sample number between the two studies could also contribute to the observed differences in aggregation indices. Plant density and distribution can have a significant influence on insect population density and spatial structure (Bach 1980, Southwood 1989).

Spatial autocorrelation analysis indicated that RWW populations generally exhibited spatial dispersion patterns that changed with population density, suggesting that spatial patterns exhibited by RWW life stages may be density dependent. Correlograms are useful in describing the autocorrelation coefficient-geographic distance relationship, and can be used to infer spatial dispersion patterns of organisms (Legendre & Fortin 1989). Inference of spatial dispersion patterns can be made by examination of the correlogram. For example, low order (short distance) positive correlations suggest aggregation, while high order (long distance) positive correlations indicate recurrence of patches within the array (Sokal & Oden 1978b, Legendre & Fortin 1989). Low order negative correlations indicate the boundary of patches or an avoidance phenomenon and high order negative correlations suggest a larger patch size or coupled with short order positive correlations, a spatial gradient (Sokal & Oden 1978b, Legendre & Fortin 1989). Spatial correlograms indicated that spatial patches were a common feature exhibited by all RWW life stages for many of

the sample periods. The spatial correlograms in this study indicated that RWW populations exhibited patch sizes about 2 to 13 m^2.

The spatial density maps indicated that distinct density gradients for all RWW life stages were present; however, the spatial correlograms generally did not show this phenomenon. These apparently conflicting results probably arise because the field was rectangular (24.4 x 6.8 m) and autocorrelation at distance classes greater than 5.8 m were not examined. Autocorrelation analyses were not conducted at distances greater than 5.8 m because there would have been too few sample pairs for statistically meaningful analyses.

Aggregation was not detected by Taylor's power law or Iwao's patchiness regression, and was detected only occasionally by *k* from the negative binomial distribution. In contrast, spatial autocorrelation analysis detected significant spatial dependence for all RWW life stages. Similar results were reported by Midgarden et al. (1993) who found that Taylor's power law, Iwao's patchiness regression, and the coefficient of dispersion gave similar results, that were in opposition to the results obtained from spatial autocorrelation analysis of western corn rootwoom adults. Sun and Fleeger (1991) also reported contrasting results between a traditional spatial dispersion index and spatial autocorrelation analysis. However, Williams et al. (1992) reported that spatial autocorrelation analysis and *k* from the negative binomial distribution produced similar results when studying the spatial distribution of the wireworm, *Limonius californicus*. Traditional methods may give unpredictable

results when evaluating spatial dispersion patterns of animals (Williams et al. 1992, Schotzko & Knudsen 1992).

In this study, three traditional methods for determining spatial distribution and spatial autocorrelation analysis were used to evaluate spatial and temporal dispersion patterns of RWW populations. The traditional statistical methods for determining spatial distributions did not reliably detect RWW spatial aggregation. In fact, Taylor's power law and Iwao's patchiness regression did not detect spatial structure for any of the RWW life stages. Spatial autocorrelation analysis; however, detected significant spatial dependence for all RWW life stages. These results do not suggest that traditional statistical methods for evaluating spatial distributions of animals are not useful, but that they are limited in their ability to detect underlying spatial patterns of animals. Traditional statistical methods for inferring spatial distribution are valuable in estimating population parameters (mean and variance) which are used in the development of insect-pest sampling plans (Southwood 1989, Binns & Nyrop 1992).

Results of this study are limited to drill-seeded rice production. Other methods of rice production (i.e. water-seeding) are quite different from drill-seeded rice production practices (Anonymous 1987). The differences between these rice production methods may influence the spatial and temporal dispersion patterns exhibited by RWW populations. Additional research is needed to address these questions.

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SUMMARY

The objectives of this study were to determine the spatial and temporal distribution of and develop an accurate and economically efficient sequential sampling plan for rice water weevil (RWW), *Lissorhoptrus oryzophilus* Kuschel, in drill-seeded rice in Louisiana. Spatial distributions of RWW larvae were determined using the aggregation indices *b* from Taylor's power law, β from Iwao's patchiness regression and *k* from the negative binomial distribution. Three sequential sampling plans, the SPRT and 2-SPRT (sequential probability ratio tests), and Kuno's fixed precision sequential sampling plan were constructed from spatial distribution data for RWW larvae and evaluated relative to each other and to the current recommendations for making RWW larvae management decisions of 10 samples/field in Louisiana. Additionally, spatial autocorrelation analysis was used to evaluate the spatial and temporal dispersion patterns of RWW adults, eggs, larvae and pupae, and the results compared to those obtained from three traditional methods for determining spatial distribution; i.e. Taylor's power law, Iwao's patchiness regression, and *k* from the negative binomial distribution. This was done because spatial autocorrelation analyses rely on geographic location of individual data points, while traditional methods for determining spatial patterns rely on variance-mean relationships. Thus, spatial autocorrelation analyses may give better insight to the underlying spatial patterns of animals relative to traditional methods for determining spatial distributions.

The aggregation indices, *b* from Taylor's power law, β from Iwao's patchiness regression and *k* from the negative binomial distribution data indicated that RWW larvae exhibited a near random distribution regardless of sample date or population density. A common *k* (*kc*) of 13.63 was determined from larva data collected over all sample dates, and did not significantly deviate from the negative binomial distribution. The *kc* determined from our data also indicated that RWW larvae were nearly randomly distributed.

Although both Taylor's power law and Iwao's patchiness regression indicated that larvae followed a near random distribution, analysis of our data indicated that Iwao's patchiness regression fit RWW larva distributions better than Taylor's power law. The poor fit of Taylor's power law to larva distributions limits its use for development of realistic sampling plans. The aggregation parameters from Iwao's patchiness regression and the negative binomial distribution fit the larva data well and could be used to develop accurate and more efficient sampling plans for RWW larvae.

Three sequential sampling plans for RWW larvae were constructed and evaluated for sampling efficiency and accuracy. Kuno's fixed precision sequential sampling plan was constructed using Iwao's patchiness regression parameters and specified precision levels of D=0.20 and 0.30. Monte Carlo simulations of Kuno's sampling plan provided actual precision levels, at economic threshold for RWW larvae, that were higher than those specified for the simulation. These results indicate that greater than necessary sampling effort is expended at the specified precision

levels. This could be alleviated by adjusting the specified precision levels until the desired precision levels are obtained. Kuno's sampling plan required, at the specified precision levels of D=0.20 and 0.30, ≈ 6 and 14 samples to estimate RWW larva economic threshold, respectively.

The *kc* determined from the larva data was used to construct the sequential probability ratio tests (SPRT and 2-SPRT). Monte Carlo simulation of the SPRTs indicated that the 2-SPRT generally required fewer samples to make terminating decisions for RWW larvae management compared to the SPRT. This difference occurs primarily because of the convergent decision boundaries of the 2-SPRT. The SPRT and 2-SPRT required an average of 2.43 and 2.59 samples to make terminating management decisions at RWW larvae economic threshold. Although the 2-SPRT generally required less sampling effort compared to the SPRT, only the SPRT maintained Type I and II error rates below the specified error rates of 0.10.

Of the three sequential sampling plans tested in this study the SPRTs required the least sampling effort, while Kuno's fixed precision sequential sampling plan required the greatest. The effort required to take and process samples for RWW larvae are time consuming and costly. Thus, Kuno's plan would probably not be adopted for commercial use, but could be useful when accurate estimation of RWW larva density is necessary. Of the two SPRTs tested, Wald's SPRT required greater sampling effort, but produced lower Type II error rates. Both SPRT procedures; however, performed reasonably well and could substantially decrease sampling effort

compared to current RWW larva sampling programs employed to make RWW management decisions in Louisiana.

Spatial autocorrelation analysis, *b* from Taylor's power law, β from Iwao's patchiness regression and *k* from the negative binomial distribution were used to evaluate the spatial and temporal dispersion patterns of RWW adults, eggs, larvae and pupae. Aggregation indices from Taylor's power law and Iwao's patchiness regression indicated that RWW were nearly randomly distributed regardless of developmental stage, density, or sample date. Values of *k* indicated that RWW populations generally exhibited clumped distributions at the lowest RWW densities, otherwise k values were in agreement with Taylor's power law and Iwao's patchiness regression.

Spatial autocorrelation analysis indicated that all RWW developmental stages exhibited significant spatial dependence. Spatial correlograms and spatial density maps indicated that 4 to 13 m^2 patches were exhibited by all RWW developmental stages. This spatial phenomenon were not detected by Taylor's power law, Iwao's patchiness regression or *k* from the negative binomial distribution. These results indicate that traditional methods for determining spatial distribution are limited in their ability to detect spatial patterns of animals.

The spatial density maps indicated that distinct density gradients for all RWW life stages were present; however, the spatial correlograms generally did not show this phenomenon. These apparently conflicting results probably arise because the field

was rectangular (24.4 x 6.8 m) and autocorrelation at distance classes greater than 5.8 m were not examined. Autocorrelation analyses were not conducted at distances greater than 5.8 m because there would have been too few sample pairs for statistically meaningful analyses.

VITA

Mark Alan Muegge was born in Greenfield, Indiana to Richard and Barbara Muegge on September 18, 1956. He graduated from Greenfield Central High School in 1975 and began part-time study at Indiana University-Purdue University at Indianapolis in 1977. He transferred to Purdue University in 1981 where he graduated with a B.S. in entomology in 1983. After employment as a laboratory technician at Purdue University, he traveled to the University of Tennessee where he obtained a M.S. in entomology in 1987. He remained at the University of Tennessee as a research assistant until 1989 when he accepted a research associate position at Louisiana State University under Dr. Sharron Quisenberry. He began studies on the spatial distribution and sequential sampling of rice water weevil in 1992 to obtain his Ph.D. under the direction of Dr. James D. Barbour.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Mark Alan Muegge

Major Field: Entomology

Title of Dissertation: Spatial Distribution and Sequential Sampling of the Rice Water Weevil, *Lissorhoptrus oryzophilus*, Kuschel in Louisiana

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

Dec 2 1995